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PROPERTIES OF NEW HIGH-TEMPERATURE TITANIUM ALLOYS

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PROPERTIES OF NEW HIGH-TEMPERATURE TITANIUM ALLOYS

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SUMMARY

This memorandum compares and summarizes the compositions, recommended heat treatments, and basic physical and mechanical properties for a group of 12 relatively new titanium alloys. Most of these were developed for service above 600 F as bar and forging alloys and can be considered as alloys of the "super" alpha class. These include the Ti-6Al-2Sn-4Zr-2Mo, Ti-5Al-5Sn-5Zr, and Ti-7Al-12Zr compositions, which were developed in the United States, as well as the series of IMI-679, -680, -EX 684, and -EX 700 alloys and of Hylite 50, 51, 55, 60, and 65 alloys, all of which were developed in the United Kingdom. In addition, some preliminary data are presented for a silicon-modified version of the Ti-6Al-2Sn-4Zr-2Mo alloy.

INTRODUCTION

This memorandum was prepared to acquaint the U.S. defense metals community with the existence and basic properties of a relatively new group of 12 titanium alloys. Most of these alloys were designed principally as bar or forging alloys to serve at moderately high temperatures, i.e., from 600 to 1200 F, and most can be considered as alloys of the "super" alpha class. These include three compositions that were developed in the United States and nine that were developed in the United Kingdom.

For reader convenience, the first section of this memorandum identifies and compares the physical properties of these alloys as well as their room- and elevated-temperature tensile and creep properties for a selected condition of heat treatment. Succeeding sections of this memorandum are devoted to each of the alloys individually. These sections contain a brief description of each alloy's forging characteristics, recommended heat treatments, and additional mechanical-property data, usually for several conditions of heat treatment.

PROPERTY COMPARISIONS

Composition

Table 1 lists the producers and compositions of 12 alloys described in this memorandum. As indicated, three of these alloys were developed and/or are being produced in the United States by the Titanium Metals Corporation of America (TMCA) and/or Reactive Metals Incorporated (RMI). The nine remaining alloys were developed in the United Kingdom by the Imperial Metal Industries Limited (IMI) or by Jessop-Saville Limited (Jessop). The IMI Alloy 679 is also produced in the United States by TMCA under license from IMI.

At the time this memorandum was being prepared, word was received(1) that, as of early November, 1967, IMI had purchased all of Jessop's titanium patents and titanium interests and that Jessop, accordingly, was discontinuing production of its Hylite series of titanium alloys. Of the various Hylite alloys that had been produced, DMIC also understands that IMI presently only intends to continue production of the Hylite 50 and 51 compositions under the designations of IMI 550 and 551, respectively. Nonetheless, DMIC has retained property data for the Hylite 55, 60, and 65 alloys in this memorandum in the belief that an appreciable inventory of these alloys still exists and the possibility that production of these alloys may be renewed at a later date.

As noted in the introduction, most of these alloys were developed for service at temperatures above 600 F. Accordingly, all of these contain substantial quantities of aluminum (which stabilizes the alpha allotrope of titanium to temperatures above 1620 F) and tin and/or zirconium (which are essentially neutral with respect to altering the temperature of the allotropic modification). Indeed, two of these alloys (Ti-5-5-5 and Ti-7-12) use these combinations of alloying additions alone. Because of their lack of beta-stabilizing alloying additions, neither of these alloys is heat treatable, and both are characterized by excellent thermal stability and weldability.

Most of the remaining 10 alloys also contain a small quantity (1 to 4 percent) of molybdenum, which acts to stabilize the beta allotrope of titanium. This results in the formation of a small quantity of the beta phase as a normal microstructural constituent in these alloys over their service-temperature range. It also makes these alloys amenable to property changes through solution and aging heat treatments. Because their total beta-stabilizer content is small — especially in proportion to their combined aluminum, tin, and zirconium content — these alloys are regarded as "near-alpha" or "super-alpha" alloys.

The two earlier Jessop alloys (Hylite 50 and 51, now designated as IMI 550 and 551, respectively) are exceptions to the above near-alpha or super-alpha alloy classification. Because of their proportionately higher beta-stabilizing alloy content, these two alloys are appreciably more responsive to heat treatment than the others and can be regarded as roughly equivalent to the Ti-6Al-4V alloy in this regard. Accordingly, the IMI-550 and 551 alloys show a lesser degree of thermal stability than the super-alpha alloys.

One further distinguishing characteristic of the British developed alloys is that all of these contain from 0.2 to 0.5 percent of silicon. According to an IMI spokesman(2), the principal function of the silicon addition is to improve the hot strength of titanium by solid-solution strengthening.

Physical Properties

Table 2 summarizes the available data on density, coefficient of thermal expansion, electrical resistivity, and thermal conductivity of the

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alloys listed in Table 1. For purposes of further comparisons, Table 2 also includes these data for the Ti-6Al-4V, Ti-5Al-2.5Sn, and Ti-8Al-[illegible] 1V alloys, which are the alloys in greatest usage in the United States today.

Mechanical Properties

This section contains selected mechanical-property data for the 12 alloys of Table 1 as well as for the three leading U. S. produced alloys, i.e., Ti-6Al-4V, Ti-5Al-2.5Sn, and Ti-8Al-1Mo-1V. In order to afford as direct a property comparison as possible, an effort was made in the compilation of these data to seek values obtained from bar stock and/or forgings of equivalent size. Also, in most cases, a single heat-treatment condition corresponding to the manufacturer's recommendation was used. For Ti-6Al-4V alloy, property data are only given for the mill-annealed condition.

Tensile

Table 3 presents a summary of the room-temperature tensile properties for all of the alloys under consideration. Except for the Ti-7-12 data, which were obtained from forgings, all of these data were obtained on bar stock. Sizes of the bar stock and the heat treatments used are given in the footnotes. Figures 1-4 compare the tensile properties of these alloys at temperatures to 1300 F.

Creep

The data on creep properties are incomplete, and in general, data from different laboratories are not directly comparable. Figure 5 shows a Larsen-Miller plot for 0.2 percent creep deformation of Ti-6Al-2Sn-4Zr-2Mo, compared to several other American alloys and the Ti-679 alloy. All of the specimens were taken from compressor-wheel forgings.

Strictly comparable data for the three IMI alloys could not be located. Figure 6 shows some creep data for the three alloys. Whether these alloys were in bar form or from forgings when tested was not specified. Moreover, while the data points for Alloys 680 and EX 679 are comparable, those for Alloy 684 are not.

The three Jessop Hylite alloys are compared to each other and to IMI 679 and Ti-6Al-4V in Figure 7. These data are for bar stock and appear to be strictly comparable.

Finally, another tensile creep comparison of seven alloys (including Ti-6Al-4V, Ti-7Al-4Mo, Ti-8Al-1Mo-1V, Ti-6Al-2Sn-4Zr-2Mo, Ti-5Al-5Sn-5Zr, IMI 679, and Hylite 60) was made by Coyne and Sparks(4). As shown in Figure 8, the workers commented that of the alloys in this grouping, "the compositions which appear to have the best combination of tensile strength, creep resistance, and creep stability are the Ti-6Al-2Sn-4Zr-2Mo and Hylite 60. Both of these alloys were stable up to 1000 F for the stresses and times investigated. The Ti-5Al-5Sn-5Zr alloy also showed excellent creep resistance and creep stability; however, the tensile strength of this alloy was significantly lower than those of the other alloys.

INDIVIDUAL ALLOY PROPERTIES

Ti-6Al-2Sn-4Zr-2Mo

The alloy Ti-6Al-2Sn-4Zr-2Mo is produced by TMCA, and only data supplied by TMCA in References 3 and 15 are quoted here. The forging characteristics of the alloy are rated "fair to good" in its forging range of 1675 to 1775 F by Wyman-Gordon engineers.(4) A compressor-wheel forging 20.0 in. in diameter, weighing 60 pounds, with a 2-1/2-in. rim and a 3/4-in. web has been described by them.

Recommended Heat Treatments

Heat treatments recommended by TMCA(3) for bar and forged sections of alloy Ti-6Al-2Sn-4Zr-2Mo are:

> Sections less than 2-1/2-in. diam --1750 F/1 hr, AC + 1100 F/8 hr, AC
>
> Sections greater than 2-1/2-in. diam --1650 F/1 hr, AC + 1100 F/8 hr, AC, or 1750 F/1 hr, AC + 1100 F/8 hr, AC.

The manufacturer states: "The 1650 F solution treatment, in combination with an 1100 F, 8 hr stabilization anneal, provides somewhat higher tensile strengths at room and elevated temperatures, while 1750 F solution treatment with the same low temperature stabilization anneal results in superior creep resistance at the higher temperatures, improved stability, and somewhat higher room-temperature notched-stress-rupture strength."

Tensile Properties

The ultimate tensile strength, 0.2 percent offset yield strength, and elongation of specimens taken from a forged compressor wheel are shown in Figure 9. Data on this curve from Reference 3 appear nearly identical with those in a table in Reference 15. Reference 15 shows that there is very little difference in the properties of a specimen taken on a bar whose axis parallels the forging axis and one whose axis is in a radial direction in the forging, except for data points on reduction of area at 800 F. Reduction-of-area data and room-temperature notched-stress-rupture data from Reference 15 are quoted on the next page. Heat treatment of this forging was the same as for that shown in Figure 9. The producer guarantees that this alloy will exceed a 170-ksi 5-hour room-temperature notched-stress-rupture requirement.

Similar data from Reference 15 illustrate the higher strengths obtainable with another heat treatment: 1750 F/1 hr, water quench, + 1100 F/8 hr, air cool. After this treatment, the room-temperature tensile and yield strengths were, respectively, 167.5 and 151.2 ksi with 11 percent elongation, while the comparable data at 1000 F were 114.9 ksi, 89.3 ksi, and 22.3 percent. Again, there was little difference between specimens from either direction in the forging. The faster cooling (quenching) increased the tensile strength, but is said to decrease the creep resistance.

Creep Strength

A Larsen-Miller plot of creep data for this alloy with both of the above recommended heat

Test Temp., F	Direction[a]	RA. percent	Room-Temp Notched-Stress-Rupture (K_t=4.0) Propertie	
			Stress, ksi	Hours
Room	A	38.2	190	3.3
	R	31.9	190	2
800	A	34.0		
	R	57.2		
1000	A	64.5		
	R	63.1		
1100	A	63.2		
		64.4		

(a) A designates testing on bars whose axes parallel the forging axis;
R designates bars whose axes are radial directions in the forging.

treatments is shown in Figure 10. Typical creep curves are shown in Figure 11.

Elastic Modulus

The tensile modulus of elasticity from room temperature to 1000 F, as determined on an experimental lot processed to 1/2-in. bar, is shown in Figure 12.

Ti-6Al-2Sn-4Zr-2Mo-Si

Modification of the basic Ti-6Al-2Sn-4Zr-2Mo composition by silicon additions is being considered by TMCA as a means of improving this alloy's hot strength.(23) While neither the silicon level nor heat treatments have yet been optimized, limited data (see Figure 13) indicate that a significant gain in creep strength of this alloy can be effected by silicon additions on the order of 0.15 to 0.25 percent. Tables 4 and 5 present some tensile and creep properties of the alloy modifications under study by TMCA and also illustrate the effects of various forging and heat treatments on these properties.

Ti-5Al-5Sn-5Zr

The forging characteristics of Ti-5-5-5 have been rated as "poor to fair" over the range of 1700 to 1800 F.(4) One such forging, 31.5 in. in diameter, weighing 662 pounds, with a maximum section size of 13 in. in the coupling and a minimum of 1 in. in the web, has been described in the literature.(4)

The alloy is of interest for its high creep strength and stability at elevated temperatures. The Aerospace Structural Materials Handbook(20) states: "Among the super-alpha titanium alloys under current (Dec. 1963) evaluation, it is by far the most stable, its limit of stability under stress being, for example, 1100 F (the maximum temperature studied to date), whereas the Ti-8Al-1Mo-1V shows stability to 950 F."

The same source also notes that while the Ti-5-5-5 (sheet) alloy is not as strong in tension tests as the Ti-8-1-1 alloy over the entire temperature range to 1100 F, the former is considerably stronger in creep. "For example, the stress required to produce 0.2 percent creep in 100 hours at 950 F for the duplex-annealed Ti-8Al-1Mo-1V alloy is 31 ksi, whereas for the mill annealed Ti-5Al-5Sn-5Zr alloy, the stress is 51 ksi."

Recommended Heat Treatments

Either a simple single anneal cycle or a duplex anneal is recommended for the Ti-5-5-5 alloy. For forgings, these are (a) 1650 F/4 hr, AC, or (b) 1750 F/1 hr, AC + 1300 F/8 hr, AC. The first produces the highest creep strength; the second gives somewhat higher short-time tensile properties between 600 and 800 F, but reduced creep properties. The duplex treatment also tends to produce a higher rupture strength.(16)

Tensile Properties

Tensile properties of compressor-wheel forgings of Ti-5-5-5 alloy after each of the above recommended heat treatments are shown in Figures 14 and 15. The data appear to represent average strengths of rim and web sections, all taken in radial directions.

Unnotched-and notched-stress-rupture data of compressor-wheel forgings from the same heat are shown in Tables 6 and 7.

Creep Strength

Creep data for the Ti-5-5-5 alloy with two different conditions of heat treatment were determined at 850, 950, and 1050 F.(16) Stress-versus-time curves from these data were established and are given in Figures 16 and 17.

Elastic Modulus

Data for modulus determinations on bar of the Ti-5-5-5 alloy are shown in Figure 18.

Ti-7Al-12Zr

Coyne and Sparks,(4) and Greenlee and Broadwell(16) have reported fairly extensive tests on forgings of this alloy. Coyne and Sparks rated the forging characteristics of the Ti-7-12 alloy as "fair to good" in its forging range of 1700 to 1800 F. A compressor-wheel forging was reported to have a wheel diameter of 31.5 in., a weight of 668 pounds, and maximum and minimum section sizes of 13 in. in the coupling and 1 in. in the web, respectively.(4)

Recommended Heat Treatments

Two heat treatments have been suggested for the Ti-7-12 alloy a simple anneal, 1600 F/4 hr, AC; and a duplex anneal, 1750 F 1 hr, AC + 1300 F/8 hr, AC. In general, the properties of the alloy after either of these treatments were similar, but the duplex 1700 F-1300 F anneal provided a slight rupture-strength advantage over the simple 1600 F anneal.(16)

Tensile Properties

The short-time elevated-temperature tensile properties of specimens taken from a 21-1/2 x 1-1/2-inch compressor-wheel forgings after each of the recommended heat treatments are shown in Figures

19 and 20. The specimens from which the data were obtained were taken from both radial and tangential sections in the rim and high-coupling areas and the junction of coupling and wheel mid-radius, and in a few instances from the small-coupling area of the forging. These data were found to be in excellent agreement with similar data from Reactive Metals(20) for the Ti-7Al-12Zr alloy.

Creep Strength and Thermal Stability

Stress-rupture data from Reference 16 are shown in Table 8. The advantage of the duplex anneal in improving stress-rupture properties is evident from these data. However, the Larsen-Miller parameter-versus-stress curves for creep, given in Figures 21 and 22, indicate that only a slight advantage is gained in creep properties of Ti-7-12 alloy by the use of the duplex anneal.

Results of creep tests on specimens from a compressor-wheel forging at another laboratory are shown in Figure 23.

Table 9, indicates that exposures to elevated temperatures under stress have little effect on the subsequent strength at room temperature, but that the ductility may be reduced.

IMI 679

(Ti-2.25Al-11Sn-5Zr-1Mo-0.2Si)

As noted earlier, this alloy was originally developed by Imperial Metal Industries Limited at its Kynoch Works in Birmingham, England and is also produced in the United States by TMCA, who holds a license from the British Company. Wyman-Gordon has noted that the alloy has good forgeability.(24)

Recommended Heat Treatments

The 679 alloy may be solution treated from a range of temperatures between 1550 and 1675 F. As a 1700 F solution temperature is approached, ductility values are lowered as illustrated by the data of Table 10. The effect of cooling rate from the solution temperature is particularly important for this alloy, with fast cooling (as by water quenching) being favored to obtain the largest strength increases (see Tables 11 and 12). Considering these points, a preferred solution treatment of 1650 F has been recommended(17) with holding times to 1 hour for larger sections. Termination of the solution treatment by water quenching is recommended if high tensile strength is the required criterion. If improved tensile ductility and elevated-temperature creep strength are the requirements, air cooling from the solution temperature may be desirable. The latest (August 9, 1966) information received from IMI (Reference 25) states that, "Nowadays, the U.K. industry uses material of substantial section in the solution treated, oil quenched, and aged condition with a consequent improvement in strength levels."

The recommended aging treatment is 24 hours at 930 F followed by air cooling.

Tensile Properties

The tensile properties of forgings of IMI 679 alloy, as reported from four independent sources, are shown in Figure 24. The differences reported are not great, although very large forgings have lower strengths than smaller ones.(26)

Wyman-Gordon(24) found IMI 679 alloy stock from either TMCA or IMI identical in forgeability, and also found that the properties of the forgings were practically identical. The tensile properties of compressor-wheel forgings from both sources are shown in Table 13.

Lockheed(26) tested specimens cut from a modified F-104 aft fuselage ring fitting. They found only minor variations in tensile properties with grain direction or location. "The IMI alloy was exceptionally uniform and exhibited a minimum range in tensile properties... Values of elongation and reduction of area were very high at all locations and test temperatures in the...forgings. The lowest values measured at room temperature were... 10.5 percent elongation and 30 percent reduction of area..."

Notched-tensile properties of IMI 679 forgings at room temperature are shown in Table 14. Although the theoretical stress-concentration factor (K_t) is not the same in the two types of forgings, the differences in notched strengths are so great that it appears that the oil quench following solution heat treatment and the processing in the first group must have had a beneficial effect on notched tensile strength.

Results of notch-time-fracture tests by Wyman-Gordon are shown in Table 15.(24) Most of the same data, with a slightly different arrangement, are included in Reference 17.

Creep Strength and Thermal Stability

Table 16 gives creep data on Alloy 679 compressor forgings from various sources, and Figure 25 shows a Larsen-Miller plot for the same material, based on results obtained by TMCA.(17) Stress-rupture strengths from TMCA and the General Electric Company are given in Table 17 and Figure 26, respectively.

The stability of 679 alloy heat treated in the form of jet-engine compressor wheels has been found to be good at least up to temperatures of 900 F as shown by the data given in Table 18. Instability for this alloy has been found at 950 F and 1000 F exposures in 100 hours or less. Since the greatest variation in stability appeared at 950 F, this appears to be the threshold temperature for instability. Results of tests at 900 F exposure temperature indicated no instability for times up to 1000 hours.

Elastic Modulus

The variation of elastic modulus with temperature of IMI 679, as reported by IMI, is shown in Figure 27. Determinations of modulus at room temperature as reported by other laboratories are listed below:

Form	Heat Treatment	Modulus Tension, 10^6 psi	Modulus Compression, 10^6 psi	Reference
2-1/4 in. bar stock	1650 F 1 hr, AC + 930 F 24 hr, AC	15.[illegible](a) 15.4	 --	19 19
Forging	1650 F 1 hr, fan cool + 930 F 24 hr, AC	15.[illegible](a)	16.1(a)	26

(a) Values obtained with Tuckerman gage

IMI 680

(Ti-2.25Al-11Sn-4Mo-0.2Si)

Titanium IMI Alloy 680 is a heat-treatable forging alloy of the alpha-beta type for which three outstanding properties are claimed:(7)

(a) Very high strength at room temperature --185-195 ksi typical tensile strength

(b) Excellent depth hardenability--specification properties can be developed throughout sections up to 8 inches thick

(c) Good creep properties up to 850 F. The alloy shows less than 0.1 percent total plastic strain in 100 hours at 750 F under a stress of 80 ksi.

The alloy is not considered to be weldable.

The manufacturer claims that IMI Alloy 680 is suitable for airframe structural forgings such as undercarriage components, engine mountings, wing-slat tracks, wing-attachment brackets, and numerous other components. It may also be used in other applications, such as turbine or compressor disks and blades where combinations of high-, room-, and elevated-temperature tensile strengths with creep resistances up to 750 F are required.

Billets for forging are available up to 12 inches in diameter. Bars for machining, either round or rectangular, that have been forged and heat treated are also available. However, this material required at least a 3:1 reduction at the recommended forging temperature to achieve the minimum guaranteed properties.(7) The manufacturer states that it is necessary to forge IMI 680 in the alpha-plus-beta field and recommends a preheating temperature of 1600 F. The resistance to deformation lies between that of IMI 679 and Ti-6Al-4V at their respective forging temperatures. A minimum of 75 percent reduction in the alpha-plus-beta field is required to achieve good ductility in the forging. Heating above the recommended forging temperature, particularly during the later stages of forging, leads to lower property levels.(7)

Recommended Heat Treatments

The recommended heat treatments for IMI 680 depend on section size and strength level desired. At strength levels above 210 ksi in rod and 200 ksi in large forgings, the ductility suffers. The recommended heat treatments were designed to give a mean tensile strength of 185-195 ksi for pieces up to 4 inches in diameter, and a mean tensile strength of 181-186 ksi at the center of larger billets. The recommended heat treatments for forgings (which differ somewhat from those for bars) are shown in Table 19.(7)

Normally, the aging treatment, 24 hours at 930 F, is carried out before machining operations. Therefore, it is recommended that the forgings be processed as shown below to remove major defects that might act as stress raisers and cause cracking during rapid cooling. If machining is carried out before the solution heat treatment, Steps (a) and (b) may be omitted.

Before solution heat treatment, the forging should be:

(a) Shot blasted to remove oxide scale and pickled to reveal any forging defects

(b) Surface dressed locally to grind out defects that would act as stress raisers during cooling

then, (c) Solution heat treated and cooled

(d) Aged

(e) Shot blasted and pickled again to facilitate final inspection.

A stress-relief treatment, 2-4 hours at 930 F, is recommended for machined components during final machining or grinding, preferably when the part is as near to final size as possible.(7)

Tensile Properties

Typical room-temperature mechanical properties of IMI 680 in various finished sizes are shown in Table 20. The effect of temperature on a fully heat-treated specimen (size and heat treatment not stated) is shown in Table 21. Tables 22 and 23 show the results of tests on forgings for production. The compressor disk of Table 22 was 13 inches in diameter with a 1-inch-thick web. Evaluation of the steering-arm forging (15 inches long x 6 inches wide) was carried out in a French laboratory.

Table 24 shows the effect of the notch concentration factor on the notched-tensile strength to tensile strength ratio of IMI 680 rod heat treated 1470 F/1 hr, WQ + 930 F/24 hr, AC. The tensile strength of the rod was 191.1 ksi.

The relation between the notched and unnotched strengths of IMI 680 after various solution treatments is given in Table 25. Increased tensile strengths were produced by increasing the solution-heat-treatment temperature. Heat treatment was carried out on 1/2-inch-square coupons cut from 3:1 upset-forged transverse slices from 5-inch-diameter billet. The coupons were water quenched from the solution-heat-treatment temperature and aged for 24 hours at 930 F and air cooled.

Creep Strength and Thermal Stability

The creep strength of fully heat treated IMI 680 up to 930 F is given in Table 26.

Exposure of IMI 680 specimens stressed at 34 ksi for 300 hours and 22 ksi for 1000 hours had no apparent effect on subsequent room-temperature strength or ductility.

Elastic Modulus

The effect of temperature on the elastic modulus of IMI 680 is shown in Figure 28. The curve shows a decided inflection point at about 250 F.

IMI EX 684

(Ti-6Al-5Zr-1W-0.2Si)

All of the available information on IMI EX 684 comes from a single bulletin issued by the manufacturer.(8) Presumably, the EX in the identification number indicates that the alloy was still considered experimental when the bulletin was issued (March 21, 1966). Provisional specifications, converted to units customarily used in the United States, are:

0.1 percent proof stress (min)	125.4 ksi
Tensile strength at 68 F (min)	143.4 ksi
Tensile strength at 970 F (min)	89.6 ksi
Elongation on 4 $\sqrt{\text{area}}$ (min)	8 percent
Reduction in area (min)	15 percent
Notched-tensile strength (K_t=3)	1.35 x tensile strength
Creep strength	Not more than 0.1 percent total plastic strain in 100 hr at 970 F under stress of 44.8 ksi.

The optimum recommended forging temperatures for IMI EX 684 are:

For heavy reductions	1920 F
For slight reductions	1795 F.

"IMI EX 684 has an unusually wide forging-temperature range and can be forged in both the alpha + beta and the beta fields, i.e., from a preheating temperature in the range 1795 to 1920 F. ...The lower temperature should be employed when only small reductions can be achieved. It is recommended that forging be discontinued when the temperature has fallen to 1650 F."(8)

Recommended Heat Treatment

The recommended heat treatment for IMI EX 684 consists of solution treatment at 1915 F for 1 hour per inch of cross section, and cooling in air (thin sections) or oil, followed by aging for 24 hours at 930 F, and air cooling.

Tensile Properties

Typical room-temperature tensile and notched-tensile properties of large forged compressor disks are shown in Table 27. The table also shows tensile properties at 970 F, as well as 100-hour creep strain at that temperature. There is little difference in tensile properties between the disk forged at 1920 F and the one at 1800 F, but the creep strain is definitely lower on the latter. Similar tensile data from two smaller disks are shown in Tables 28 and 29.

Creep Strength and Thermal Stability

Almost all of the available creep data on IMI EX 684 are shown in Tables 27 and 29. A few additional data, corresponding to the tensile data in Table 28, are shown in Table 30.

The effects of exposure time at 975 F on the room-temperature tensile properties of this alloy are given in Table 31. These data indicate that some loss of tensile ductility occurs after exposure times of 300 hours.

Elastic Modulus

The dynamic modulus of IMI EX 684 is shown as a function of temperature in Figure 29.

IMI EX 700

(Ti-6Al-5Zr-4Mo-1Cu-0.2Si)

This alloy was first introduced(9) with the nominal composition of Ti-6Al-5Zr-3Mo-1Cu-0.2Si as a bar and forging alloy for service principally in aircraft gas turbine applications at temperatures to 800 F. Subsequently, it was found that this 3 percent molybdenum version "lacked depth hardenability" and its strength "was very dependent on section size at heat treatment"(18). Consequently, the alloy was improved to a potentially stronger composition by increasing its nominal molybdenum content to 4 percent and adjusting forging and heat treatment schedules correspondingly.

Forging of the revised IMI EX 700 composition is recommended through at least a 4:1 reduction at 1650 F. Forging should be discontinued when the temperature falls below about 1470 F.(18)

Recommended Heat Treatment

The recommended solution temperature is 1520 F or 1560 F according to section thickness of the part as follows:

Section Thickness, inches	Solution Temperature, F
Up to 1.25, inch.	1520
1.25 to 2.0, inch.	1560

The solution treatment time should be not less than 1 hour for each inch of section thickness and this treatment should be terminated by oil quenching. Aging should consist of a 24 hour soak at 930 F followed by air cooling.

"There is some evidence that on occasions the ductility and notched-tensile strength of material heat treated at 1520-1560 F are low. It has been found that an extra 4 hours at solution heat treatment temperature can improve both (see Table 32)."(18) Accordingly, the 5 hour solution treatment time is suggested if poor ductility and low notched-tensile properties are encountered.

Tensile Properties

The available tensile property data on revised IMI EX 700 alloy composition are given in Table 33.

IMI 550; HYLITE 50

(Ti-4Al-2Sn-4Mo-0.5Si)

As noted earlier, the Hylite 50 alloy is an alpha-beta alloy that was developed originally by Jessop as a compressor disk or blade material and is now being produced by IMI. The alloy has also found application in structural components.

Recommended Heat Treatment

The effects of section size and cooling rates on room-temperature strength and elongation of Hylite 50 bar stock are shown in Table 34. The recommended heat treatment for Hylite 50 is to hold the alloy at 1650 F for 1 hour per inch of section thickness, followed by air cooling and then age for 24 hours at 930 F.(29) Child(21) notes that controlled slow cooling (10 F per second, maximum, over the critical range 1650 to 950 F) is essential for small forgings (compressor blades) to maintain sufficient bend ductility.

Tensile Properties

The effects of temperature on tensile properties of Hylite 50 bar stock were shown in Figures 3 and 4. Additional data on the tensile properties of Hylite 50 forgings are given in Table 35.

Creep Strength

Table 36 shows the stress required to produce 0.1 percent plastic strain, and that required to produce rupture, at selected times and temperatures, in forged bar material. The material was in the solution-treated and aged condition. Child(21) gave the stress required to produce 0.2 percent strain in 300 hours as 100 psi at 700 F and 24 ksi at 900 F.

Elastic Modulus

The modulus of elasticity in tension of Hylite 50 over the temperature range from room temperature to 1100 F is shown in Figure 30.

IMI 551: HYLITE 51

(Ti-4Al-4Sn-4Mo-0.5Si)

The titanium alloy Hylite 51 is a modification of the alloy Hylite 50, designed to have higher strength than the older alloy with similar creep properties. This was accomplished by increasing the tin content of the alloy from 2 percent to 4 percent. It is recommended for aircraft structural components and other highly stressed applications. As discussed earlier, this alloy is now available only from IMI under the designation IMI 551.

Recommended Heat Treatment

The recommended heat treatment for Hylite 51 is to anneal at 1650 F for 1 hour per inch of cross section, followed by cooling in air or oil (usually air), and age 24 hours at 930 F.(29) Bars, forgings, etc., are normally supplied in the heat-treated condition.

Tensile Properties

Typical tensile properties of Hylite 51 bar stock at various temperatures, and of a 3-inch-square billet at room temperature, are shown in Tables 37 and 38. The source notes that there is little difference between longitudinal and transverse properties on a 3-inch-square billet.

The tensile strength developed in samples from a 250-pound aircraft structural forging, heat treated after machining, is shown in Table 39. This piece was annealed for 3 hours at 1650 F, air cooled, and aged at 930 F for 24 hours. The Vickers hardness after heat treatment was 308 to 404 in the center and 411 to 425 near the edge.

Creep Strength

Table 40 shows the stress required to produce 0.1 percent plastic strain at various times and two temperatures.

Elastic Modulus

The tension modulus of Hylite 51 is shown in Figure 31 for two conditions. Water quenching after annealing and before aging increases the modulus about 1,000,000 psi over air cooling at the same stage in the heat treatment.

HYLITE 55

(Ti-3Al-6Sn-5Zr-0.5Si)

Hylite 55 is described(11) as an alloy "suitable for blading and compressor disc material for high duty conditions," being superior in creep strength to Hylite 50 above 660 F.

Recommended Heat Treatment

Bars, rough-machined discs, and forgings are supplied in the fully-heat-treated condition which consists of normalizing at 1830 F and aging for 24 hours at 930 F.(11)

Tensile Properties

Typical tensile properties obtained on bar stock of this alloy, with an average loading rate of 4,480 psi, are given in Figure 32.

Creep and Rupture Strength

The available creep and stress-rupture strength data for Hylite 55 bar stock are summarized in Table 41.

Elastic Modulus

Table 42 gives Young's tensile modulus values of Hylite 55 from 70 to 1290 F

HYLITE 60

(Ti-3Al-6Sn-5Zr 2Mo-0.5Si)

The Hylite 60 alloy is recommended for compressor disks and other highly stressed components for use at temperatures up to 930 F. The alloy is weldable and Coyne and Sparks(4) have rated the forgeability of this alloy over the forging range 1650 to 1750 F as "fair to good".

Recommended Heat Treatment

The recommended heat treatment for the Hylite 60 alloy is to anneal at 1830 F for 1 hour per inch of cross section, air cool, and age 24 hours at 1020 F, air cool. Bars, billets, and

forgings are normally supplied in the heat-treated condition.(10)

Tensile Properties

Typical short-time 0.20 percent yield stress, ultimate tensile strength, elongation, and reduction of area of Hylite 60, bar stock from room temperature to 1300 F, are shown in Figure 33. The average rate of loading in obtaining these data was 4480 psi per minute.

Wyman-Gordon forged a 10.0-inch-diameter compressor wheel of this alloy weighing 35 pounds, having a maximum section size of 2 inches in the hub and a minimum of 3/4 inch in the web.(4) Typical tensile properties from this forging are given in Table 43.

Creep Strength and Thermal Stability

Jessop-Saville recently (March, 1966) published the creep property data given in Table 44. The results of 500-hour creep tests are summarized in Table 45. The specimens for these tests were taken from 5/8-inch-diameter bar, swaged from 1.7-inch-diameter rolled rods.

Coyne and Sparks(4) have given the "typical stress-rupture value" for heat-treated* Hylite 60 under a 70-ksi load at 1000 F to be 255 hours.

These same workers(4) reported the post creep tensile results given in Table 46, after exposures of 150 hours. Except at 1020 F, there was no loss in ductility, while the strength increased in all cases.

Elastic Modulus

The tensile modulus of Hylite 60 at temperatures from 70 to 1290 F is shown in Figure 34.

HYLITE 65

(Ti-3Al-5.5Sn-5.5Zr-0.5Mo-0.5Si)

The titanium alloy Hylite 65 is a new modification of Hylite 60. The alloy has been described as "a weldable medium-strength alloy with excellent resistance to creep,and developed for service at temperatures up to 1000 F. It is intended for use in advanced jet engine compressor components such as discs, spacers and blades, and other applications where high-temperature-creep strength and weldability are required."(10)

Recommended Heat Treatment

The recommended heat treatment for Hylite 65 is the same as that for Hylite 60: 1830 F for 1 hour per inch of cross section, air cool, age 24 hours at 1020 F, air cool.

Tensile Properties

The mechanical properties of Hylite 65 are shown in Table 47 in the temperature range from 70 to 1290 F. In general, they appear to be similar to those of Hylite 60 --slightly lower over most of the temperature range but higher at the highest temperatures.

Creep Strength and Thermal Stability

Creep properties of Hylite 65 determined from tests on 1-inch-diameter bar are shown in Table 48. Limited tests are said to have shown no evidence of serious thermal instability.(10)

Elastic Modulus

The tensile modulus of Hylite 65 is shown in Figure 35.

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* 1830 F/1 hr, AC + 1020 F/24 hr, AC.

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(6) "IMI Titanium 679", Brochure IMI-Ltd, undated.

(7) "Properties of IMI Titanium 680", Brochure IMI-Ltd, undated.

(8) "IMI Titanium EX 684", Brochure IMI-Ltd, (March 21, 1966).

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(13) "Compilation of Available Information on Ti-5Al-2.5Sn Alloy", TML Memorandum (July 15, 1957).

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(20) Weiss, V., and Sessler, J. G., "Aerospace Structural Metals Handbook--SS519 Vol. II, Nonferrous Alloys", ASD TDR 63-741 (March 1963).

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(28) Erdeman, V. J., "A Titanium Alloy for Elevated Temperature Use", Metal Progress, pp 80-83 (February 1966).

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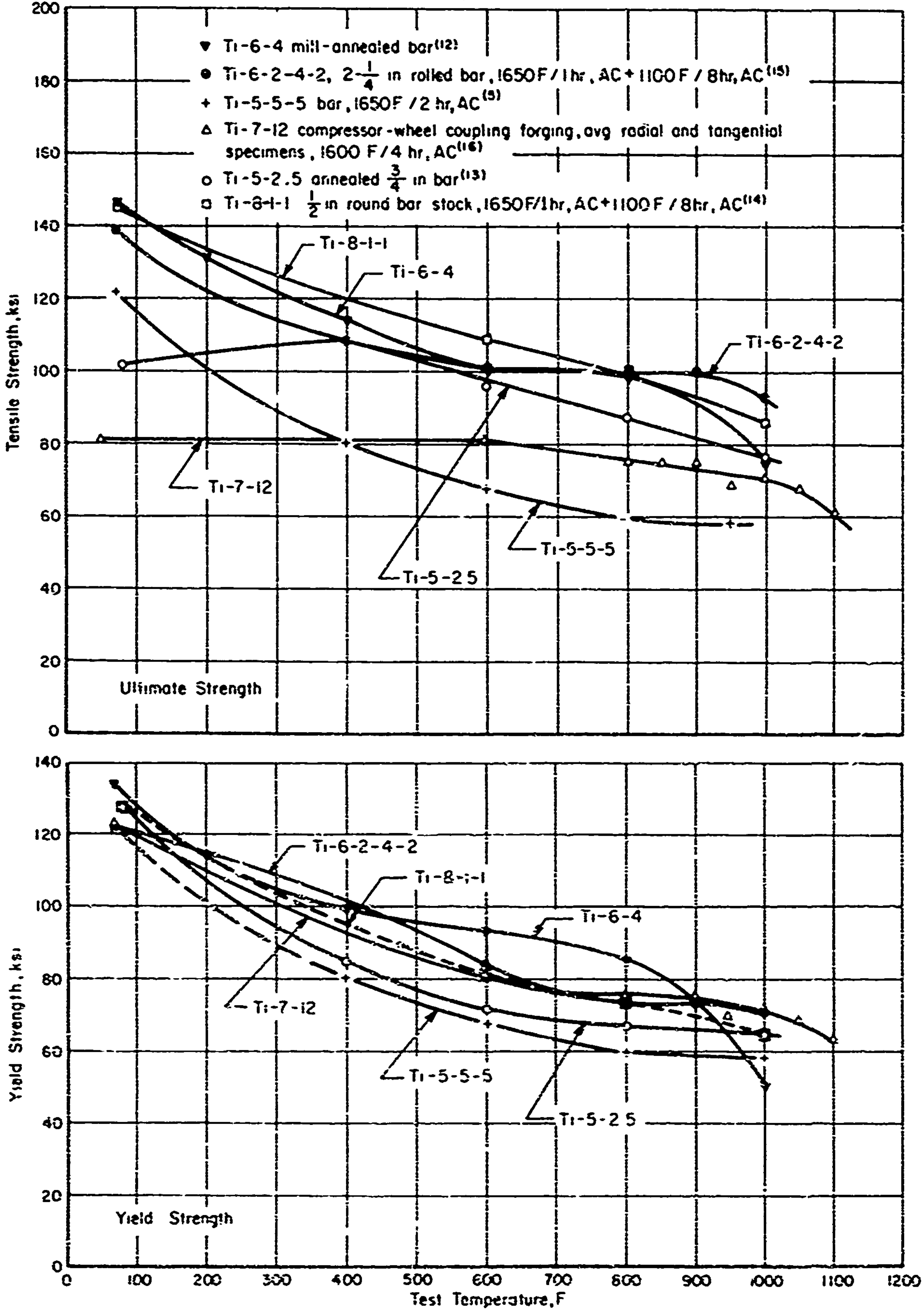


FIGURE 1. ULTIMATE TENSILE AND YIELD STRENGTH VERSUS TEMPERATURE FOR SIX U. S. TITANIUM ALLOYS

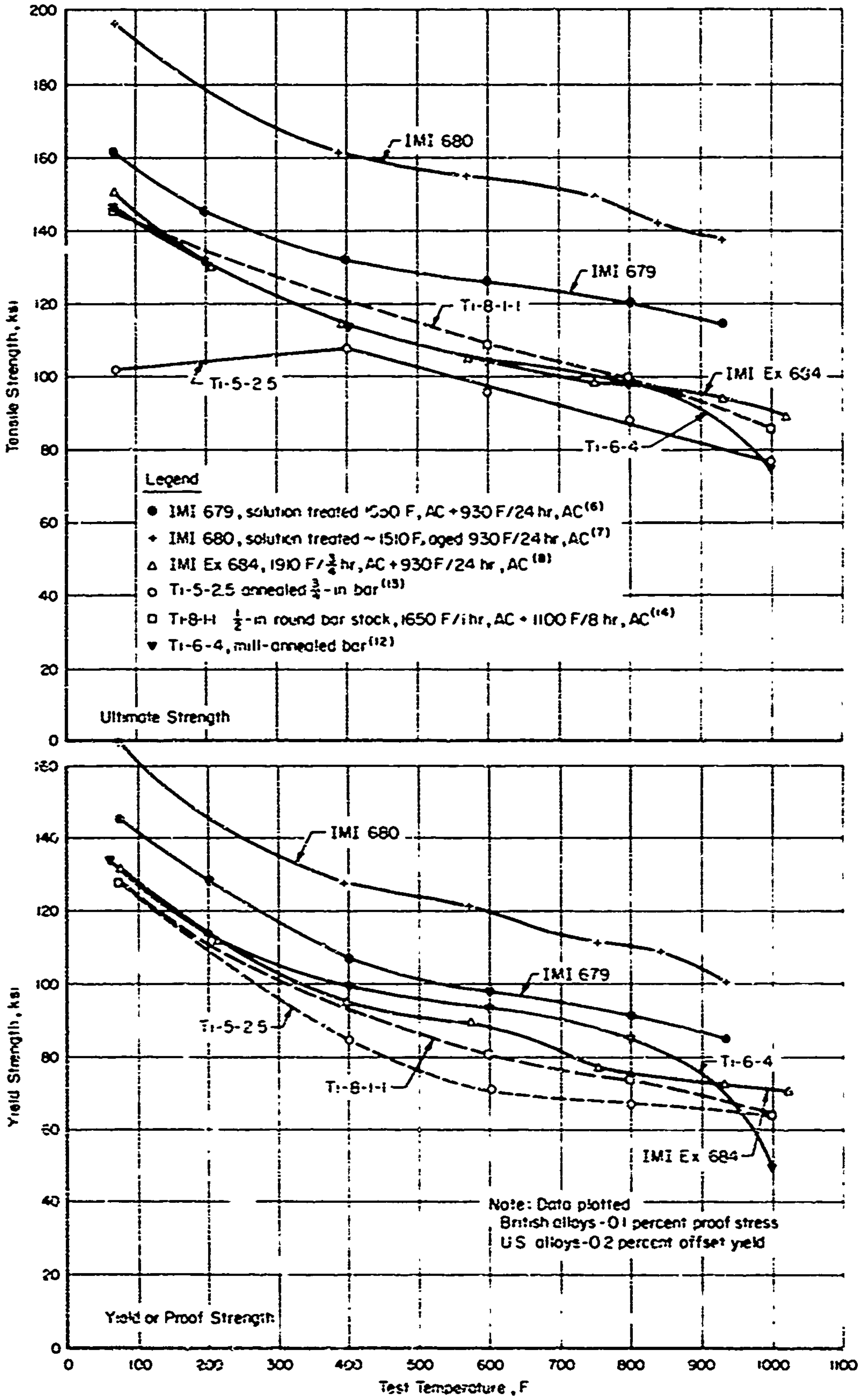


FIGURE 2. ULTIMATE TENSILE AND YIELD STRENGTH VERSUS TEMPERATURE FOR THREE BRITISH (IMI) AND THREE U. S. TITANIUM ALLOYS

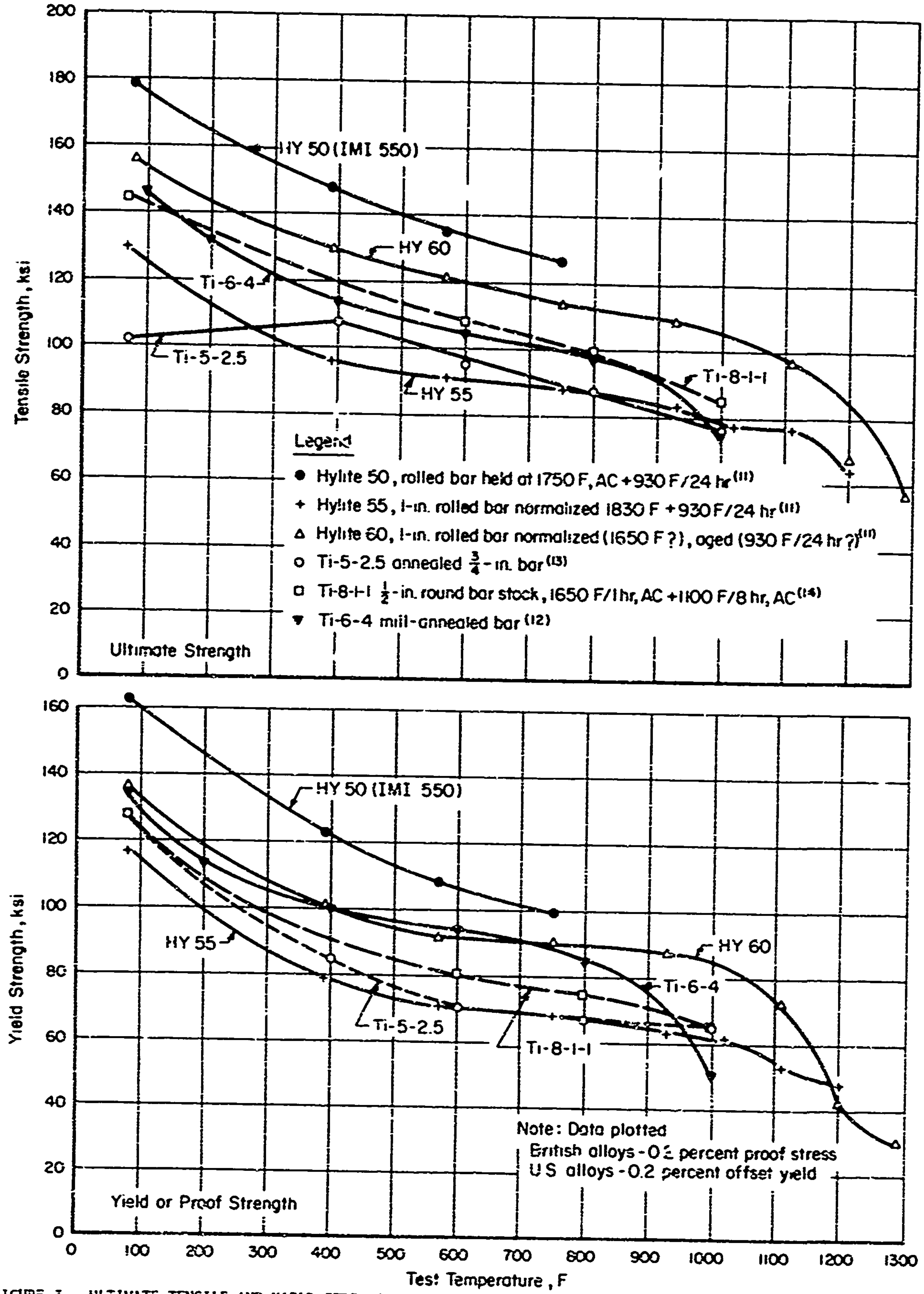


FIGURE 3. ULTIMATE TENSILE AND YIELD STRENGTH VERSUS TEMPERATURE FOR THREE BRITISH (JESSOP) AND THREE U. S. TITANIUM ALLOYS

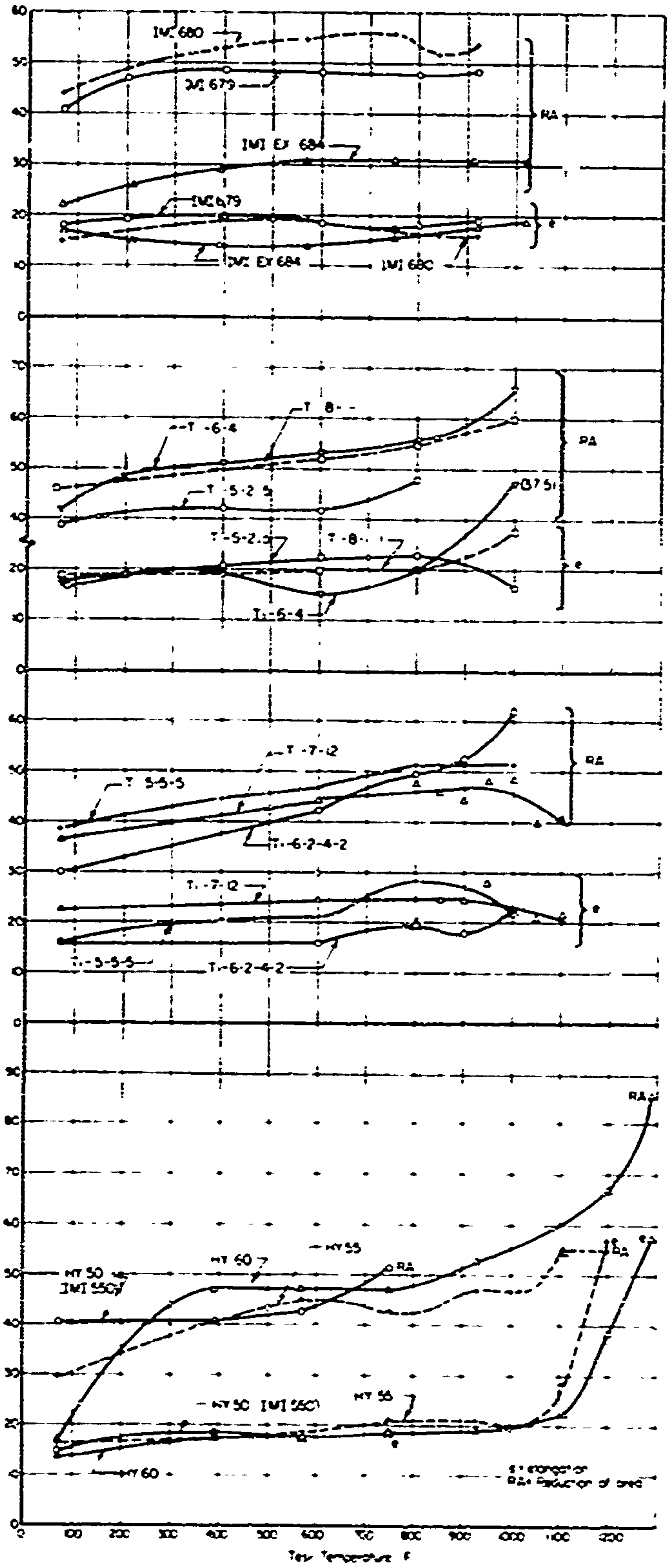
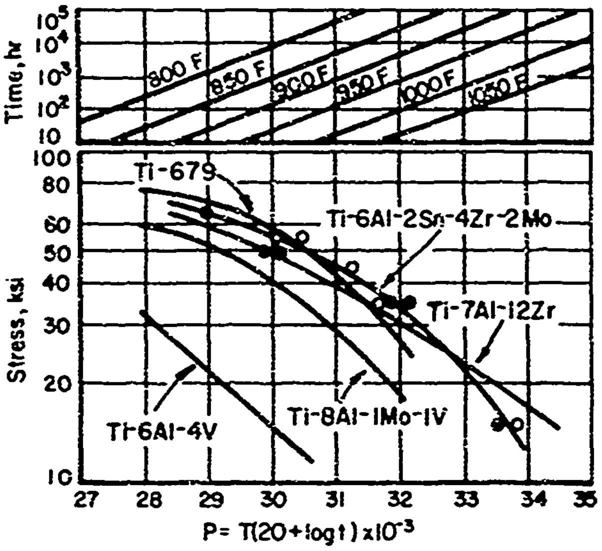


FIGURE 4. ELONGATION AND REDUCTION OF AREA OF 12 TITANIUM ALLOYS

Note: See Figures 1-3 for references and heat treatments used.



0.2 Percent Creep Deformation
Compressor-Wheel Forgings

Alloy	Density, lb/cu in.	Heat Treatment
Ti-6Al-4V	0.160	Annealed 1300 F/2 hr, AC
Ti-8Al-1Mo-1V	0.158	1850 F/1 hr, AC + 1100 F/8 hr, AC
Ti-679	0.174	1650 F/1 hr, AC + 930 F/24 hrs, AC
Ti-6Al-2Sn-4Zr-2Mo	0.164	● 1750 F/1 hr, AC + 1100 F/8 hr, AC ○ 1650 F/1 hr, AC + 1100 F/8 hr, AC
Ti-7Al-12Zr	0.164	1600 F/4 hr, AC

FIGURE 5. LARSON-MILLER PLOT OF 0.2 PERCENT CREEP DEFORMATION FOR VARIOUS ALLOYS(15,20)

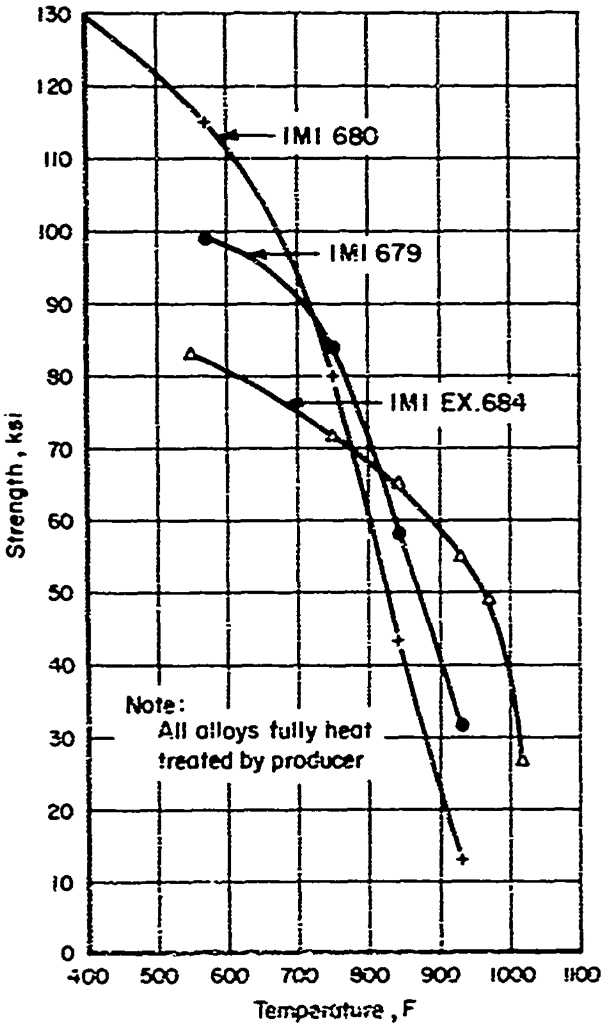


FIGURE 6. STRESS TO PRODUCE 0.1 PERCENT TOTAL PLASTIC STRAIN IN 300 HOURS IN IMI 679(6) AND IN 100 HOURS IN IMI 680(3) AND EX 684(8)

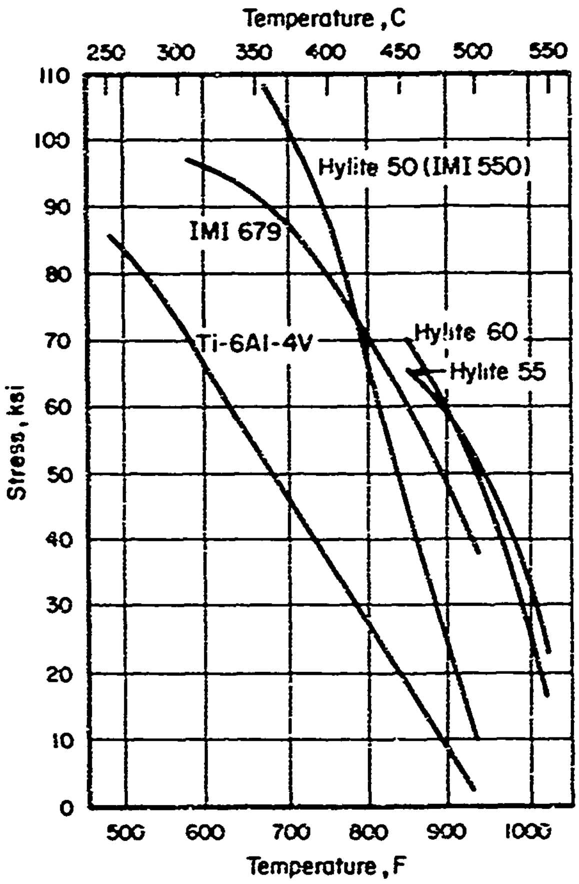


FIGURE 7. STRESS TO PRODUCE 0.2 PERCENT CREEP STRAIN IN 300 HOURS VS TEMPERATURE, 5/8-IN. DIAMETER BAR STOCK(21)

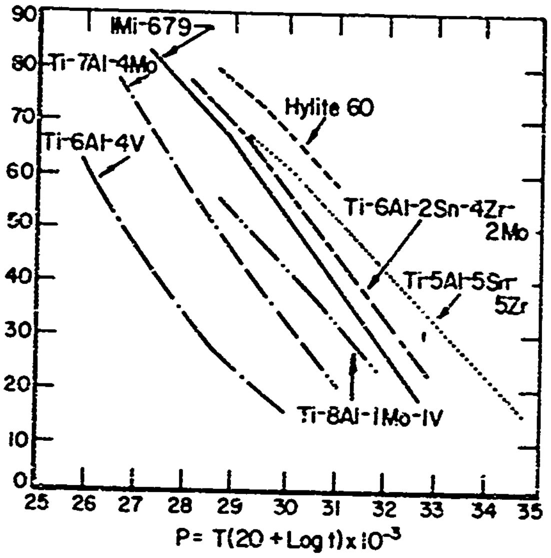


FIGURE 8. LARSEN-MILLER PLOT FOR 0.2 PERCENT PLASTIC DEFORMATION FOR SEVERAL TITANIUM COMPRESSOR-WHEEL ALLOYS(4,22)

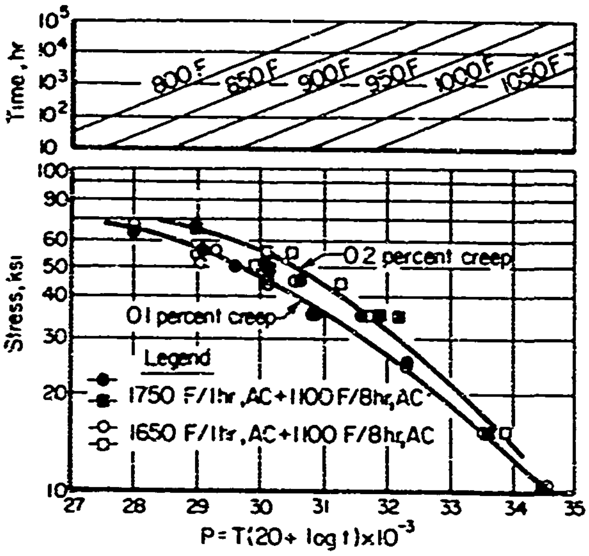


FIGURE 10. LARSON-MILLER PRESENTATION OF CREEP DATA FOR BAR AND FORGED SECTIONS OF Ti-6Al-2Sn-4Zr-2Mo(3)

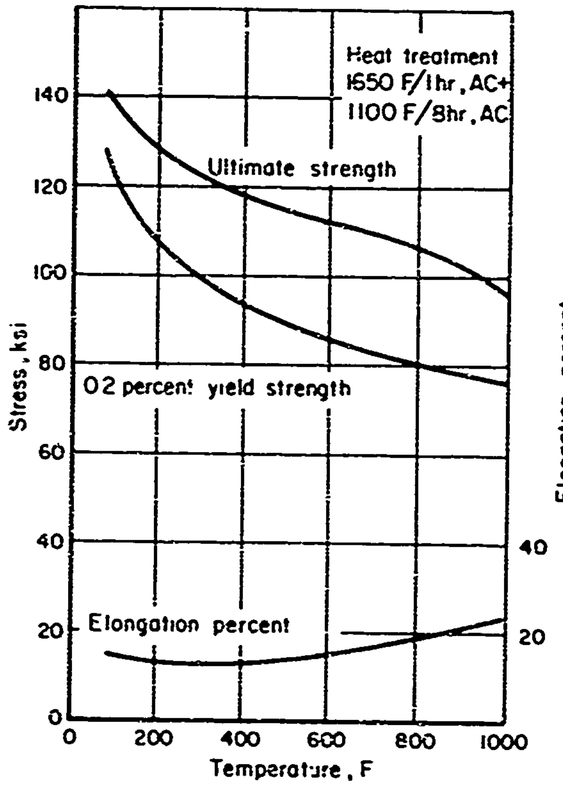


FIGURE 9. ROOM- AND ELEVATED-TEMPERATURE TENSILE PROPERTIES OF Ti-6Al-2Sn-4Zr-2Mo FORGED COMPRESSOR WHEEL(3)

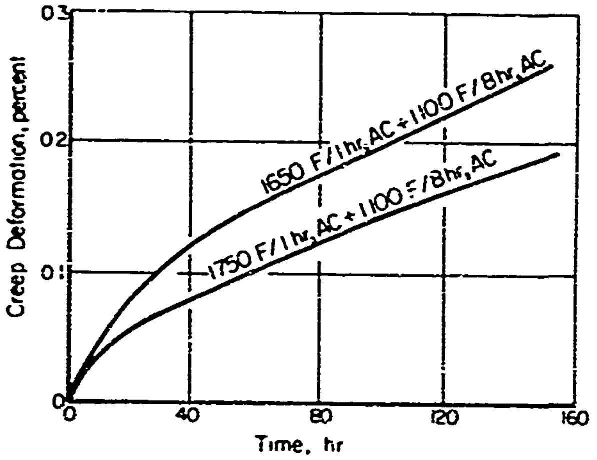


FIGURE 11. TYPICAL CREEP CURVES FOR Ti-6Al-2Sn-4Zr-2Mo FORGED SECTIONS EXPOSED AT 900 F AND 50 KSI(3)

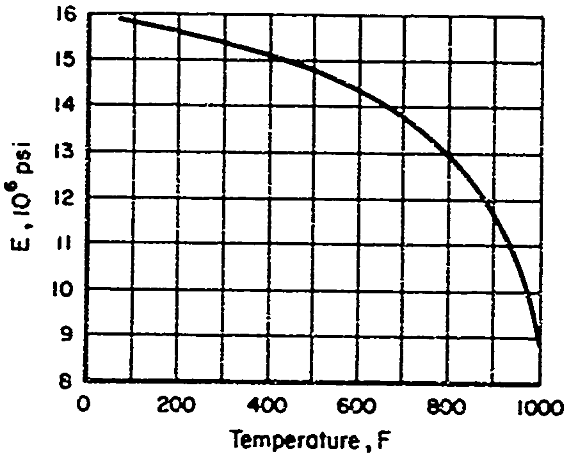


FIGURE 12. STATIC MODULUS OF ELASTICITY OF Ti-6Al-2Sn-4Zr-2Mo VS TEMPERATURE[15]

(1/2-in. Bar, 1675 F/ 1/2 hr, AC + 1100 F/ 8 hr, AC)

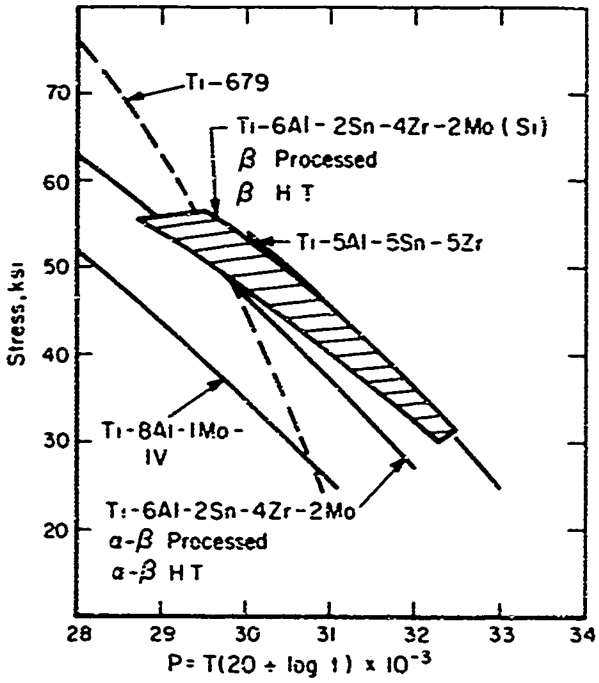


FIGURE 13. LARSON-MILLER PLOT OF 0.1 PERCENT CREEP DEFORMATION FOR SELECTED ALLOYS[23]

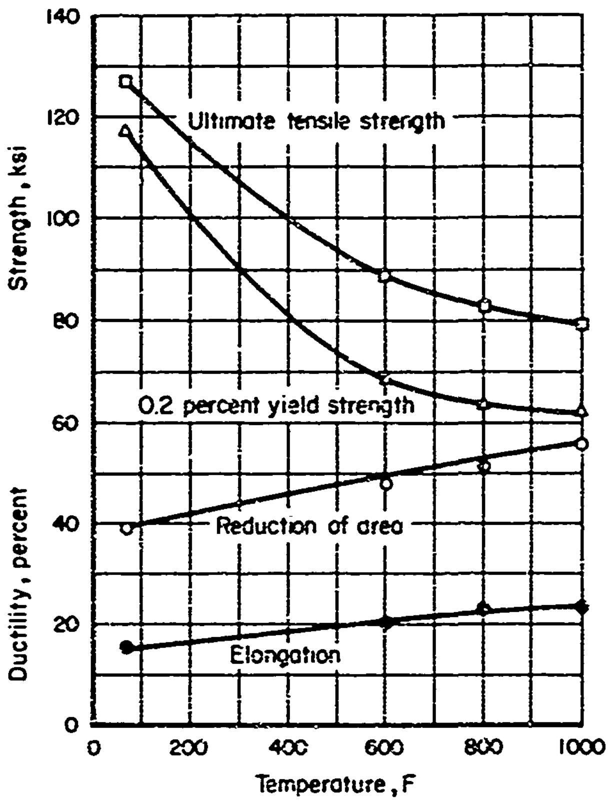


FIGURE 14. SHORT-TIME ELEVATED-TEMPERATURE TENSILE PROPERTIES OF Ti-5Al-5Sn-5Zr FROM COMPRESSOR-WHEEL FORGING; ANNEALED 1650 F/4 HR, AC[16]

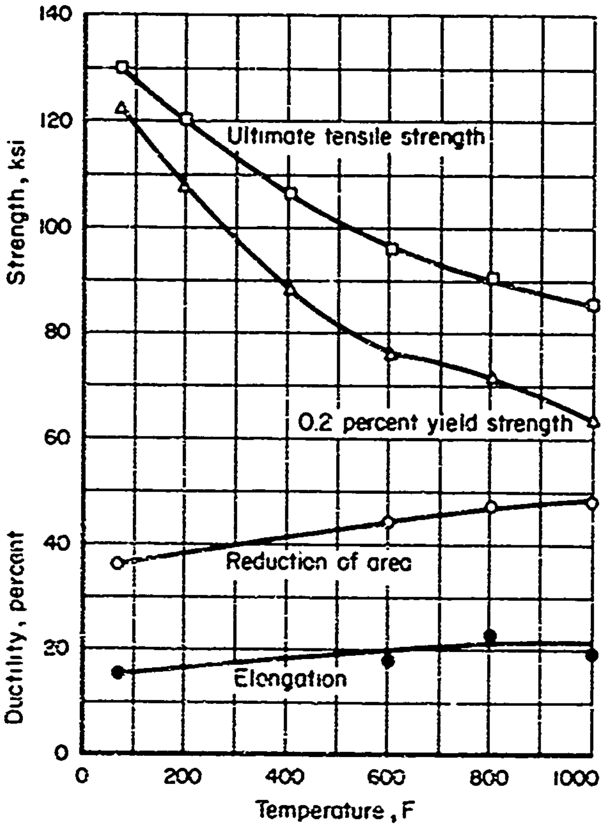


FIGURE 15. SHORT-TIME ELEVATED-TEMPERATURE TENSILE PROPERTIES OF Ti-5Al-5Sn-5Zr FROM COMPRESSOR-WHEEL FORGING; DUPLEX ANNEALED 1750 F/1 HR, AC + 1300 F/8 HR, AC(16)

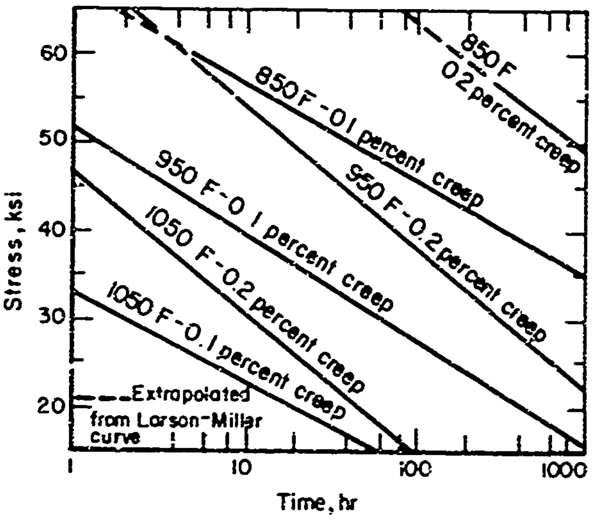


FIGURE 17. STRESS-VERSUS-TIME CURVES FOR CREEP DEFORMATION IN Ti-5Al-5Sn-5Zr FROM COMPRESSOR-WHEEL FORGING; DUPLEX ANNEALED 1750 F/1 HR, AC + 1300 F/8 HR, AC(16)

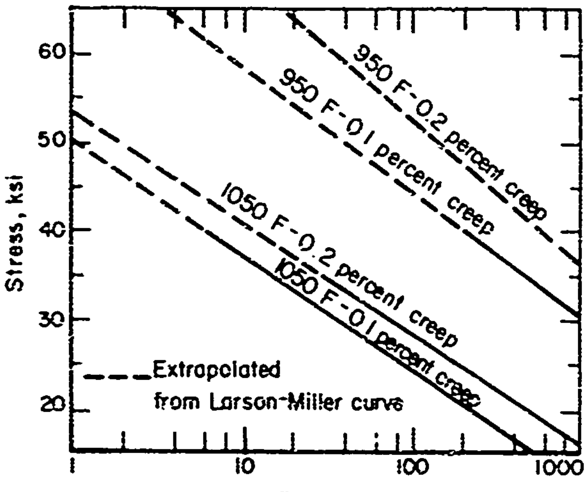


FIGURE 16. STRESS-VERSUS-TIME CURVES FOR CREEP DEFORMATION IN Ti-5Al-5Sn-5Zr FROM COMPRESSOR-WHEEL FORGING; ANNEALED 1650 F/4 HR, AC(16)

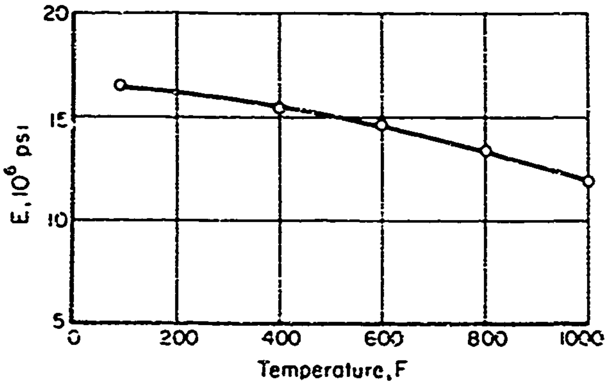


FIGURE 18. MODULUS OF ELASTICITY OF Ti-5Al-5Sn-5Zr ALLOY BAR(5)

Section size: 1/2 in. thick x 1-1/8 in. wide
Heat treatment: 1650 F/2 hr, AC

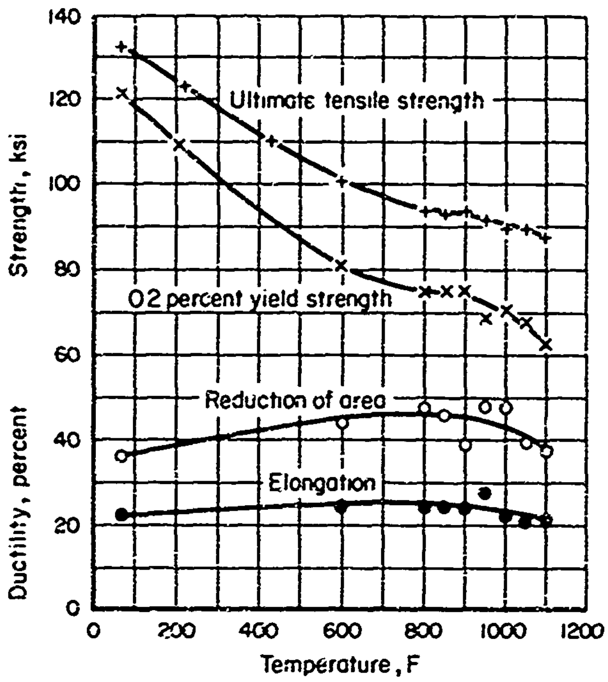


FIGURE 19. SHORT-TIME ELEVATED-TEMPERATURE TENSILE PROPERTIES OF Ti-7Al-12Zr FROM COMPRESSOR-WHEEL FORGING, ANNEALED 1600 F/4 HR, AC(16)

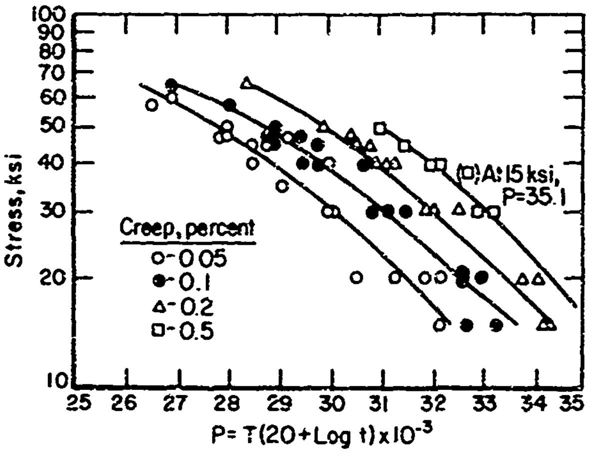


FIGURE 21. LARSEN-MILLER PARAMETER-VERSUS-STRESS CURVES FOR CREEP IN Ti-7Al-12Zr FROM COMPRESSOR-WHEEL FORGING, ANNEALED 1600 F/4 HR, AC(16)

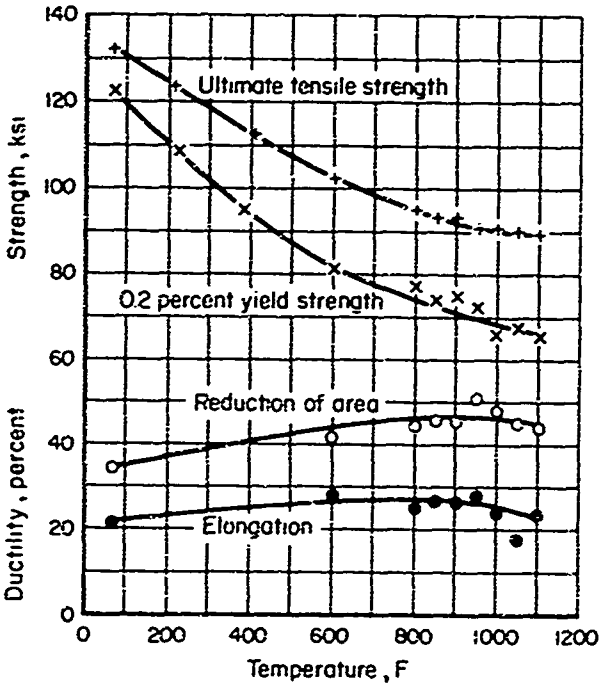


FIGURE 20. SHORT-TIME ELEVATED-TEMPERATURE TENSILE PROPERTIES OF Ti-7Al-12Zr FROM COMPRESSOR-WHEEL FORGING, DUPLEX ANNEALED 1750 F/1 HR, AC + 1300 F/8 HR, AC(16)

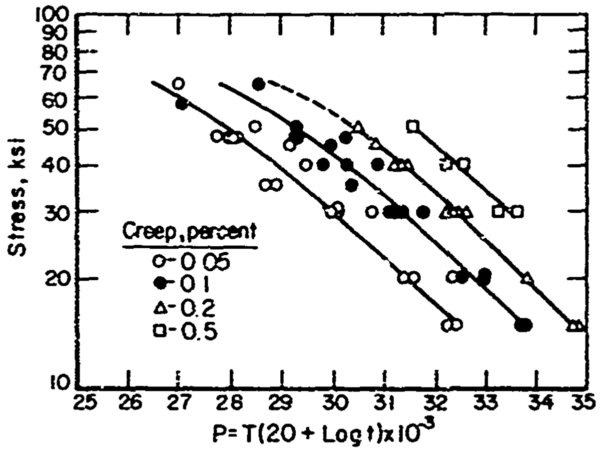


FIGURE 22. LARSEN-MILLER PARAMETER-VERSUS-STRESS CURVES FOR CREEP IN Ti-7Al-12Zr FROM COMPRESSOR-WHEEL FORGING, DUPLEX ANNEALED 1750 F/1 HR, AC + 1300 F/8 HR, AC(16)

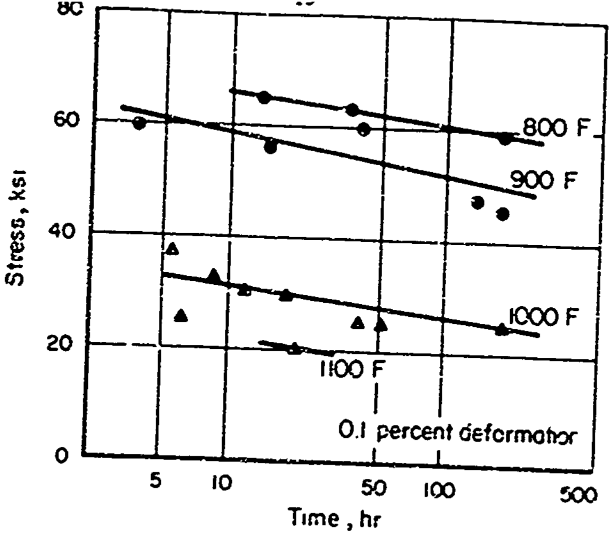


FIGURE 23. CREEP DEFORMATION CURVES AT VARIOUS TEMPERATURES FOR A Ti-7Al-12Zr COMPRESSOR-WHEEL FORGING ANNEALED 1600 F/4 HR, AC(20)

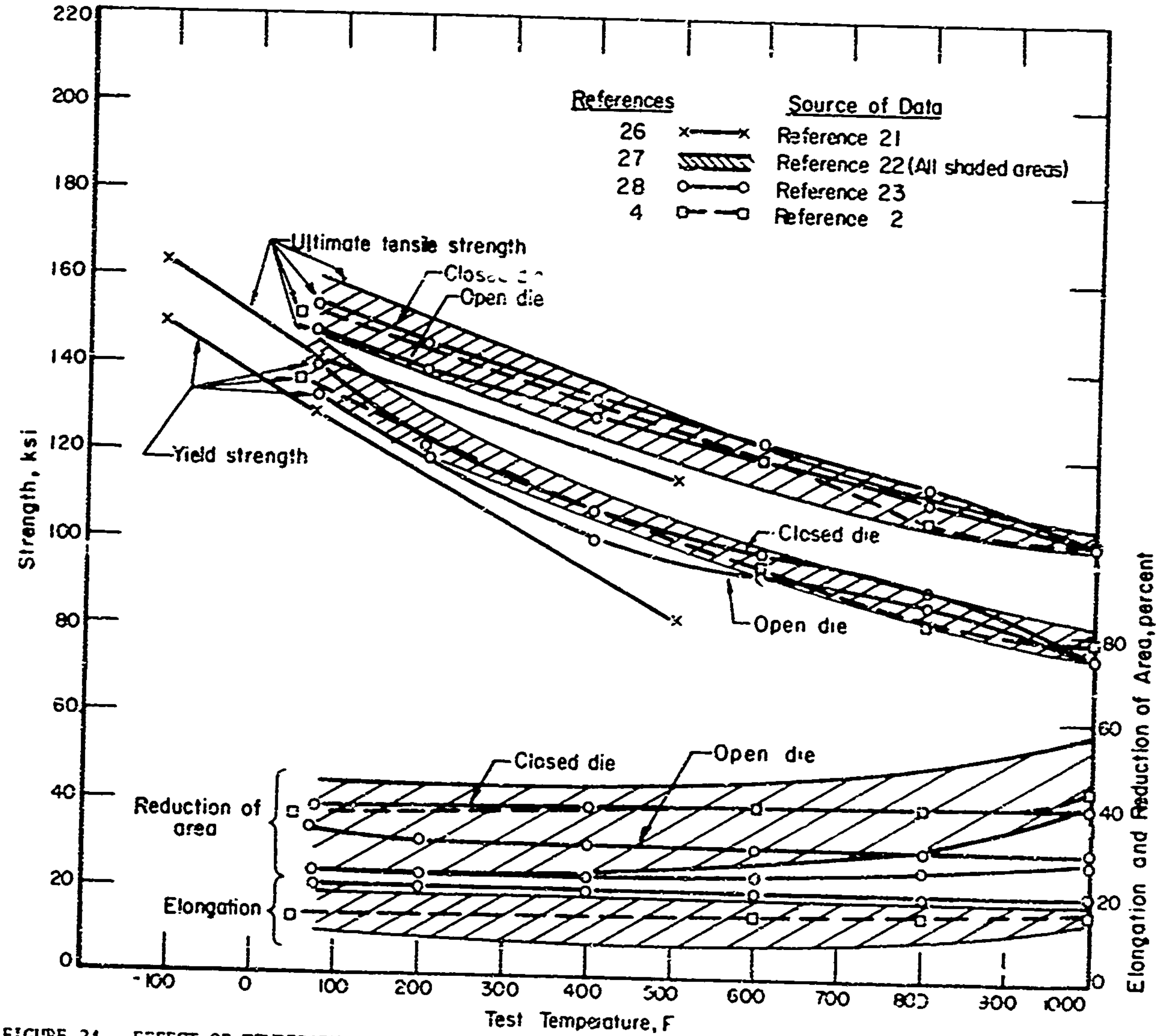


FIGURE 24. EFFECT OF TEMPERATURE ON STRENGTH OF IMI 679 FORGINGS. ALL SPECIMENS HEAT TREATED 1650 F/1 HR, AC + 930 F/8 HR, AC

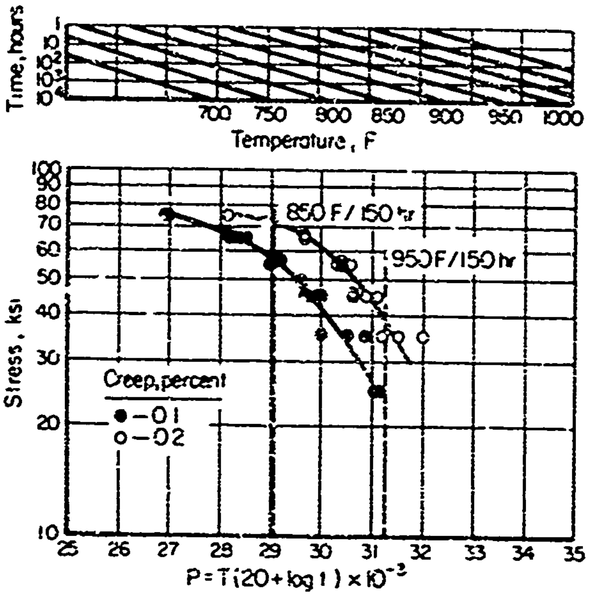


FIGURE 25. LARSEN-MILLER PARAMETER-VERSUS-STRESS CURVES FOR CREEP IN Ti-679 COMPRESSOR-WHEEL FORGINGS(17)

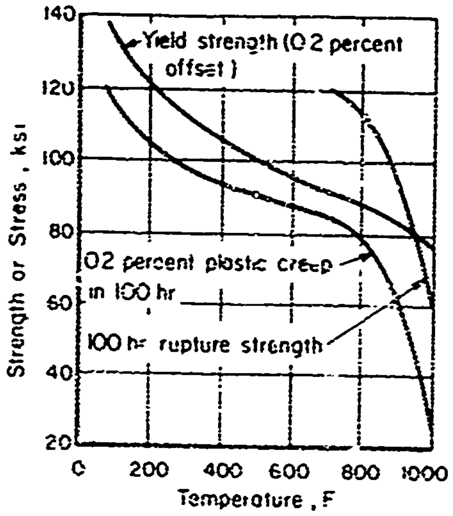


FIGURE 26. CREEP, STRESS-RUPTURE, AND YIELD STRENGTH OF Ti-679 ALLOY. INITIAL HEAT TREATMENT: 1650 F/1 HR, AC + 950 F/24 HR, AC(28)

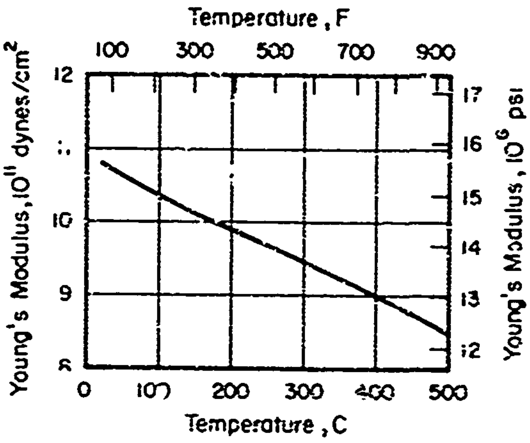


FIGURE 27. YOUNG'S MODULUS (DYNAMIC)-IMI TITANIUM 679(6)

(Specimens probably cut from bar stock, solution treated at 1650 F/1 hr, AC + 930 F/24 hr, AC)

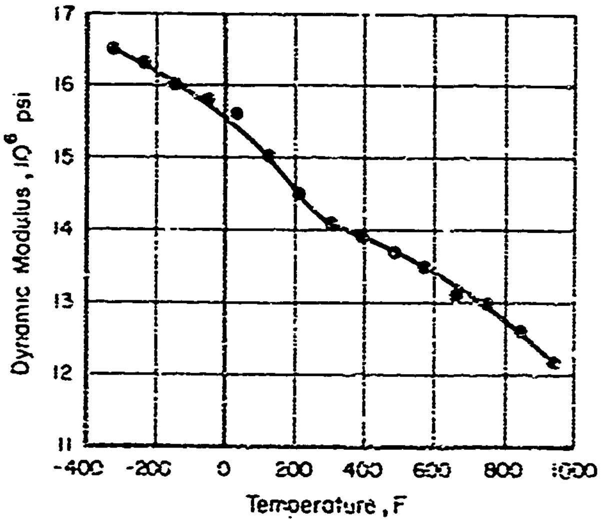


FIGURE 28. EFFECT OF TEMPERATURE ON THE DYNAMIC MODULUS OF FULLY HEAT TREATED IMI 680(7)

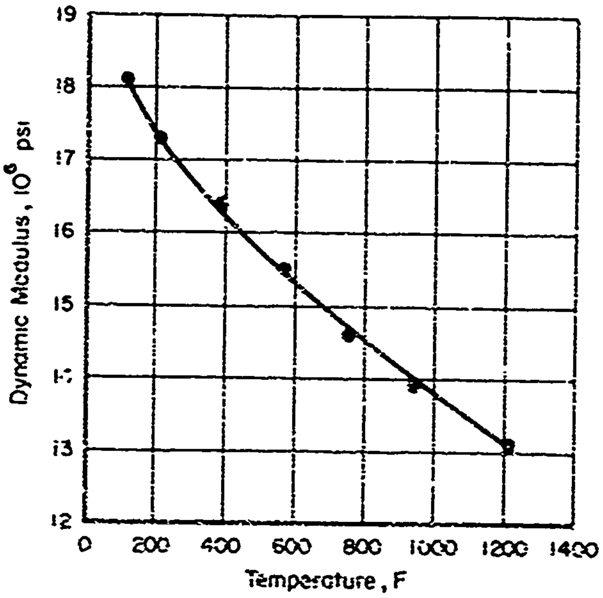


FIGURE 29. EFFECT OF TEMPERATURE ON THE DYNAMIC MODULUS OF IMI EX 684(8)

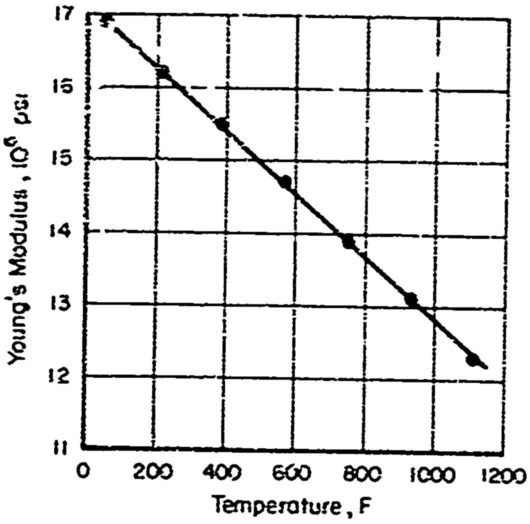


FIGURE 30. EFFECT OF TEMPERATURE ON THE YOUNG'S MODULUS OF HYLITE 50(10)

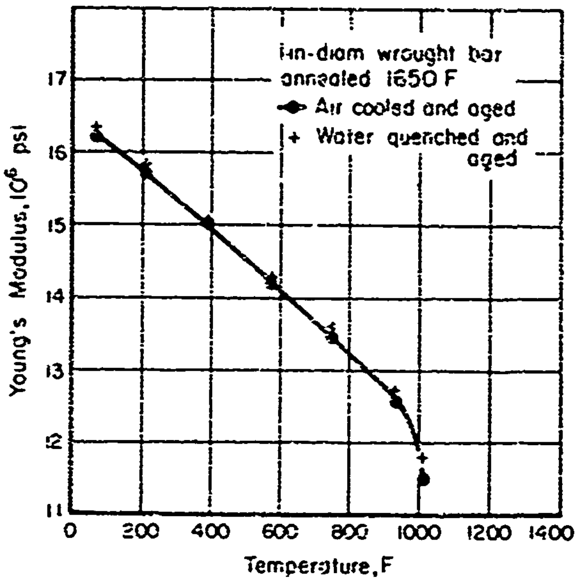


FIGURE 31. EFFECT OF TEMPERATURE ON THE YOUNG'S MODULUS OF HYLITE 51(10)

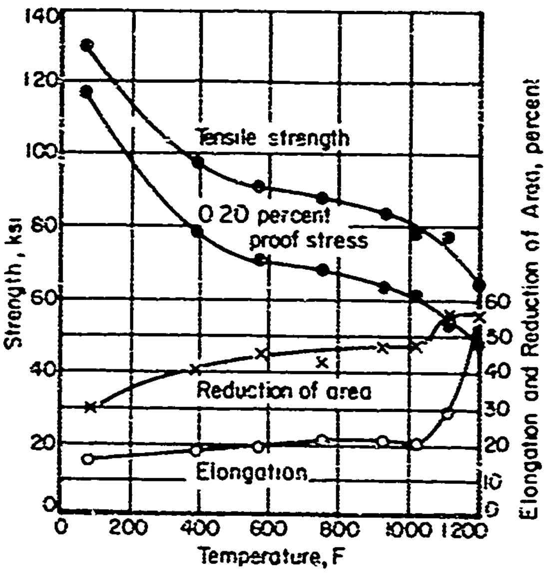


FIGURE 32. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF HYLITE 55(11)

(1-Inch-Diameter Rolled Bar, Fully Heat Treated)

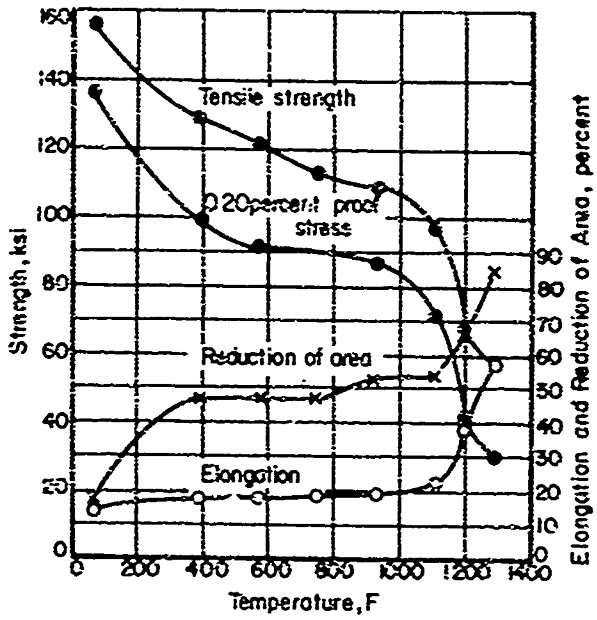


FIGURE 33. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF HYLITE 60(10)

(1-Inch-Diameter Rolled Bar, Fully Heat Treated.)

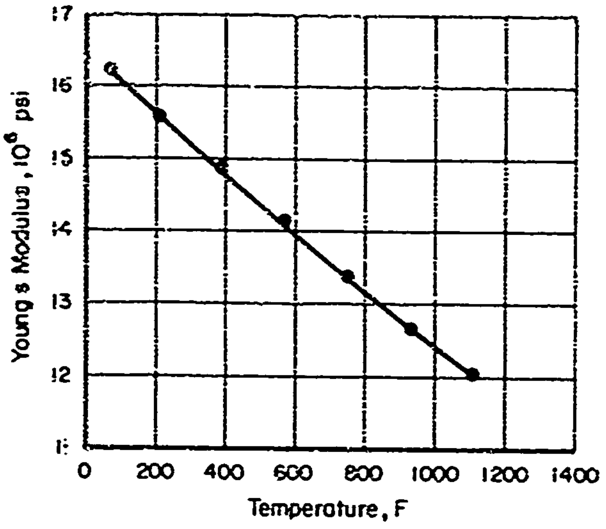


FIGURE 34. EFFECT OF TEMPERATURE ON THE YOUNG'S MODULUS OF HYLITE 60(10)

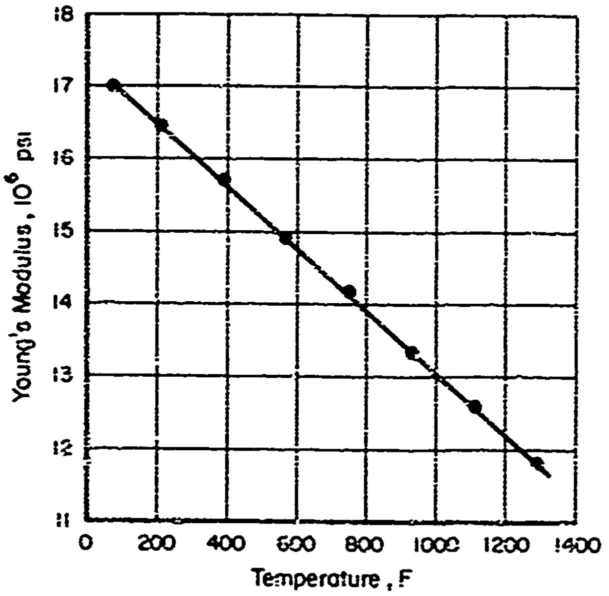


FIGURE 35. EFFECT OF TEMPERATURE ON THE YOUNG'S MODULUS OF HYLITE 65(10)

TABLE 1. NOMINAL COMPOSITIONS OF TITANIUM ALLOYS

Producer	Identification	Nominal Alloy Content, percent by weight						
		Al	Sn	Zr	Mo	Cu	Si	W
TMCA, RMI	Ti-6-2-4-2	6	2	4	2			
TMCA	Ti-5-5-5	5	5	5				
TMCA	Ti-7-12	7		12				
IMI, TMCA	679	2.25	11	5	1		0.2	
IMI	680	2.25	11		4		0.2	
IMI	EX 684	6		5			0.2	1
IMI	EX 700	6		5	4	1	0.2	
IMI[a]	IMI 550 Hylite 50	4	2		4		0.5	
IMI[a]	IMI 551 Hylite 51	4	4		4		0.5	
(a)	Hylite 55	3	6	5			0.5	
(a)	Hylite 60	3	6	5	2		0.5	
(a)	Hylite 65	3	5.5	5.5	0.5		0.5	

(a) These alloys were developed and formerly produced by Jessop-Saville Limited who recently sold all of their titanium interests to Imperial Metal Industries, Limited (IMI); See text.

TABLE 2. SELECTED PHYSICAL PROPERTIES OF TITANIUM ALLOYS

Alloy	Density		Coefficient of Expansion, 10^{-6} in./in./F	Electrical Resistivity, microhm-cm	Thermal Conductivity, Btu/ft^2/hr/F/in.	Reference
	g/cm^3	lb/in.^{3}				
Ti-6-2-4-2	4.54	0.164	4.5@ 600to1000 F	--	--	3
Ti-5-5-5	4.60	0.166	--	--	55@ 120 F, 90@ 1000 F	4,5
Ti-7-12	4.56	0.165	--	--	--	4
IMI 679	4.84	0.175	4.95@ 122to300 F	165@ 100 F	45@ 32 F, 82@ 800 F	6
IMI 680	4.84	0.175	5.1@ 70 to 570 F	165.5@ 32 F	49@ 70 F, 88@ 800 F	7
IMI EX 684	4.48	0.162	5.5@ 70 to 1110 F	--	--	8
IMI EX 700[a]	4.54	0.164	5.6@ 70 to 932 F	--	--	9
Hylite 50	4.60	0.166	5.6@ 70 to 1110 F	--	55@ 120 F, 81@ 750 F	11
Hylite 51	4.60	0.166	5.4@ 70 to 1110 F	169.9@ 68 F	46@ 70 F, 78@ 750 F	10
Hylite 55	4.76	0.172	5.3@ 70 to 1290 F	150.7@ 68 F	49@ 70 F, 84@ 750 F	11
Hylite 60	4.65	0.168	5.8@ 70 to 1290 F	153.0@ 68 F	49@ 70 F, 84@ 750 F	11
Hylite 65	4.68	0.169	5.7@ 70 to 1290 F	154.0@ 68 F	52@ 70 F, 78@ 750 F	10
Ti-6Al-4V	4.424	0.160	5.5@ 32 to 1200 F	171@ 68 F	48@ 130 F, 83@ 800 F	12
Ti-5Al-2.5Sn	4.49	0.162	5.5@ 200to1200 F	155@ 68 F	48@ 100 F, 86@ 800 F	13
Ti-8Al-1Mo-1V	4.37	0.158	6.0@ 68 to 1112 F	198.6@ 75 F	41.5@ 75 F, 77@ 800 F	14

(a) The property values cited were actually reported for the earlier Ti-6Al-5Zr-3Mo-1Cu-0.2Si version of this alloy.

TABLE 3 ROOM-TEMPERATURE TENSILE PROPERTIES

Alloy	Ultimate Tensile Strength, psi	Yield Strength 0.2 Percent Offset, psi	Elongation, percent	Reduction of Area, percent	Notes, Size and Condition	Reference
Ti-6-2-4-2	152,600	140,500	20.0	41.2	(a)	15
	138,600	121,500	16.0	30.2	(b)	15
	136,300	119,900	15.0	26.0	(c)	15
Ti-5-5-5	131,000	121,000	18.0	41.0	(d)	5
	125,000	117,500	15.0	37	(d)	5
	130,000	122,000	16.0	38.6	(e)	5
Ti-7-12 forging	132,000	121,000	22	36	(f)	16
	133,500	122,000	22	34.5	(g)	16
IMI 679	159,000	143,400	18	41	(h)	6
	177,000	150,000	13	35	(i)	6
TMCA Alloy 679	163,500	146,200	16.7	46	(j)	17
IMI 680 (billet)	188,000	152,400	10	30	(k)	7
	185,000	154,000	8.5	24	(l)	7
IMI EX 684	150,000	132,000	1	22	(m)	8
IMI EX 700	209,500	183,800	9.3	21	(n)	18
Hylite 50	179,000	162,500	15.0	40.5	(o)	11
Hylite 55	129,900	117,400	16.2	29.4	(p)	11
Hylite 60	156,100	135,200	13.9	17.0	(p)	11
Ti-6Al-4V	146,500	134,000	15.0	33.8	(q)	19
	147,500	132,000	22.0	46.6	(r)	19
Ti-5Al-2.5Sn	141,600	127,900	17	39	(s)	13
	142,600	137,300	18	15.4	(t)	13
Ti-8Al-1Mo-1V	136,500	124,500	19.0	24.4	(u)	19
	133,000	118,100	20.5	27.3	(v)	19
	130,000	120,000	10	25	(w)	14

(a) 1-1/8-in.-diam. specimen from 1-1/8-in. square-rolled bar, annealed 1650 F/1 hr, air cooled + 1100 F/8 hr, air cooled.

(b) 2-1/4 in.-diam. specimen from 2-1/4-in. square-rolled bar, annealed 1650 F/1 hr, air cooled + 1100 F/8 hr, air cooled.

(c) 2-1/4-in.-diam. specimen from 2-1/4-in. square-rolled bar, annealed 1750 F/1 hr, air cooled + 1100 F/8 hr, air cooled.

(d) Tests on bar stock from two heats performed by TMCA and reported by Southern Research Institute, sizes and heat treatments not given.

(e) Averages of ten evaluations. Heat treatment 1650 F/2 hr, air cooled.

(f) Average of six specimens, both radial and tangential, from forged compressor wheel. Heat treated 1600 F/4 hr, air cooled.

(g) Same as (f), except heat treated 1750 F/1 hr, air cooled + 1300 F/8 hr, air cooled.

(h) Typical properties. Yield at 0.1 percent proof stress, elongation on $4\sqrt{area}$, solution treated at 1650 F, air cooled, aged 930 F/24 hr.

(i) Same as (h) except oil quenched after solution treatment.

(j) Average of two specimens solution treated at 1650 F, air cooled, aged 930 F/24 hr, air cooled.

(k) Average of seven longitudinal specimens from 8-in. billet. Yield at 0.1 percent proof stress. Solution treated 1510 F, aged 930 F/24 hr.

(l) Average of seven transverse specimens from same billet as (k).

(m) Typical properties. Yield at 0.1 percent proof stress, elongation on $4\sqrt{area}$, solution treated 1910 F, 3/4 hr, air cooled + 930 F/24 hr, air cooled

(n) Average of samples taken at various locations from a [illegible]-1/2 in. thick upset forging, solution treated 1 hr at 1560 F, oil quenched, aged 24 hours at 930 F, and air cooled.

(o) Typical properties. Yield at 0.2 percent proof stress, elongation on $4\sqrt{area}$. 1-in. diam. rolled bar normalized and aged. Specific heat treatment not specified, but believed to consist of normalizing treatment at 1850 F, air cooled, + aging 930 F/24 hr, air cool.

(p) Same as (o), except usual heat treatment is normalizing at 1830 F, air cool + aged 930 F/24 hr, air cool

(q) One in.-diam. bar stock (average of two tests), heat treated 1400 F/2 hr, air cool.

(r) Bar stock, 2-1/4 in. diam. (average of two tests), heat treated 1650 F/1 hr, air cooled + 930 F/24 hr, air cooled.

(s) Averages of two tests on one annealed 3/4-in.-diam. bar.

(t) Averages of one test on each of three bars, condition not shown.

(u) Average of two tests on 1.6 x 1.9-in. bar stock. Heat treatment 1650 F/1 hr, air cool + 1100 F/8 hr, air cool

(v) Average of two tests on 1.6 x 1.9 in. bar stock. Heat treatment 1850 F/1 hr, air cool + 1100 F/8 hr, air cool.

(w) TMCA guaranteed minimum tensile properties at room temperature on bar stock up to and including 4 sq in. Data are based on either simple or duplex annealing.

TABLE 4. TENSILE AND CREEP STABILITY PROPERTIES OF FORGED Ti-6Al-2Sn-4Zr-2Mo-0.15Si BAR STOCK(23)

Hammer forged from 3-3/8-inch square to 2-1/4-inch square as indicated and annealed as 7-inch-long full sections.

Test Direction and Location	Test Temp, F	Creep Exposure	Deformation,(a) percent	Ultimate Strength, ksi	0.2% Offset Yield Strength, ksi	Elong., %	RA, %
		Forged from 1750 F and annealed at 1875 F, 1 hr., AC + 1000 F, 8 hr .					
Outside, longit.	75	None	--	145.1	123.1	13.0	23.3
Outside, longit.	1000	None	--	100.0	77.8	15.5(b)	41.1
Outside, longit.	75	850 F/70 ksi/150 hr	0.44	142.2	131.7	8.5	16.8
Outside, longit.	75	1050 F/30 ksi/150 hr	0.51	146.4	136.9	6.5	9.4
Center, longit.	75	None	--	148.2	126.7	13.0	15.3
Outside, trans.	75	None	--	147.6	126.3	11.0	20.4
Center, trans.	75	None	--	143.2	120.3	10.5	19.0
		Forged from 1900 F and annealed at 1750 F, 1 hr., AC + 1000 F, 8 hr .					
Outside, longit.	75	None	--	141.7	122.6	16.5	30.1
Outside, longit.	1000	None	--	98.4	75.1	20.0(b)	51.6
Outside, longit.	75	850 F/70 ksi/150 hr	0.39	143.7	130.4	15.0	22.7
Outside, longit.	75	1050 F/30 ksi/150 hr	0.41	146.6	130.0	13.0	16.2
Center, longit.	75	None	--	139.3	121.9	17.5	32.7
Outside, trans.	75	None	--	144.1	122.4	11.5(b)	26.8
Center, trans.	75	None	--	138.1	116.9	13.0	30.7

(a) Values determined from Vickers impressions.
(b) Broke at end of gage length.

TABLE 5. TENSILE AND CREEP STABILITY PROPERTIES OF Ti-6Al-2Sn-4Zr-2Mo-0.25Si(23)

Nominal Forging Temp., F	Heat Treatment(a)	75 F Tensile Properties				Creep Properties						Post-Creep Tensile Properties			
		Ultimate Strength, ksi	0.2% Offset Yield Strength, ksi	Elongation, %	Reduction in Area, %	Exposure Stress, ksi	Exposure Temp., F	Time to Deformation, hr 0.1%	Time to Deformation, hr 0.2%	Total Time, hrs	Plastic Def., percent	Ultimate Strength, ksi	0.2% Offset Yield Strength, ksi	Elongation, %	Reduction in Area, %
1750	β Triplex	141.8	125.2	8.5	18.8	55	900	28	280	335	0.175	143.9	132.8	7.0	11.7
		145.2	127.6	10.0	14.4	35	1000	65	155	164	0.200	144.1	137.5	7.5	9.4
1850	α/β Duplex	148.6	130.0	11.5	24.5	55	900	70	775(b)	504	0.140	152.0	135.0	12.0	21.2
		146.6	126.4	11.0	20.9	35	1000	100	225	246	0.180	148.6	133.8	11.0	19.1
1850	β Triplex	141.4	122.0	10.5	20.9	55	900	28	350	412	0.210	141.9	127.5	10.0	16.1
		142.2	124.0	10.5	21.7	35	1000	60	205	237	0.240	142.6	129.4	9.0	13.9
1900	α/β Duplex	144.8	126.0	11.0	21.7	55	900	60	870(b)	503	0.135	148.2	133.7	11.5	16.9
		141.0	118.4	11.0	23.7	35	1000	105	265	285	0.240	144.6	131.6	8.0	16.9
1900	β Triplex	141.4	125.2	10.0	20.3	55	900	30	325	360	0.210	142.6	128.8	9.0	12.3
		142.8	124.0	9.0	18.0	35	1000	55	190	213	0.185	144.2	130.1	9.0	10.9
β + 50	α/β Duplex	--	--	--	--	55	900	110	800	509	0.235	151.5	136.7	12.0	23.4
β + 50	β Triplex	--	--	--	--	55	900	45	460	503	0.140	141.8	128.6	9.0	15.4

(a) α/β Duplex = 1750 F 1 hr AC + 1100 F, 8 hr AC
β Triplex = 1850 F 1 hr AC + 1750 F, 1 hr AC + 1100 F, 8 hr AC
(b) Extrapolated data

TABLE 6. ELEVATED-TEMPERATURE STRESS-RUPTURE PROPERTIES OF Ti-5Al-5Sn-5Zr FROM COMPRESSOR-WHEEL FORGING(16)

Heat Treatment[a]	Exposure Temp., F	Exposure Stress ksi	Time to Rupture, hr
1650 F/4 hr, AC	1000	60	78.3
1650 F/4 hr, AC	1000	60	69.2
1750 F/1 hr, AC + 1300 F/8 hr, AC	1000	60	99.8
1750 F/1 hr, AC + 1300 F/8 hr, AC	1000	60	99.3

(a) Tests all in radial direction.

TABLE 7. ROOM-TEMPERATURE NOTCH-TIME-FRACTURE PROPERTIES OF Ti-5Al-5Sn-5Zr FROM COMPRESSOR-WHEEL FORGING(16)

Heat Treatment[a]	Notch Time Fracture Strength[b] Passed 5 Hr, ksi	Failure Stress, ksi	Failure Time, hr
1650 F/4 hr, AC	170	180	1.5
1650 F/4 hr, AC	180	190	0.0
1750 F/1 hr, AC + 1300 F/8 hr, AC	180	190	1.5
1750 F/1 hr, AC + 1300 F/8 hr, AC	180	190	0.9

(a) Radial specimens obtained from web of wheel.
(b) Initial stress of 130 ksi, increased by 10-ksi increments every 5 hours until failure.

TABLE 8. ELEVATED-TEMPERATURE STRESS-RUPTURE PROPERTIES OF Ti-7Al-12Zr FROM COMPRESSOR-WHEEL FORGING(16)

Code	Direction[a]	Position[a]	Temp., F	Stress ksi	Time to Rupture, hr	Elongation, percent	Reduction of Area, percent
		Heat Treated 1750 F/1 hr, AC + 1300 F/8 hr, AC					
80	Tang.	HC	900	62.5	(b)	0.5	0.0
79	Tang.	HC	1000	60	396	-	7.9
81	Tang.	HC	1000	60	274	13.8	21.9
82	Tang.	HC	1100	57.5	12.8	26.9	35.5
		Heat Treated 1600 F/4 hr, AC					
31	Tang.	Jct.	900	62.5	(b)	0.7	0.0
106	Tang.	HC	1000	60	165.2	-	19.1
95	Tang.	Rim	1000	60	150.5	29.3	24.8
107	Tang.	HC	1100	57.5	5.4	43.1	31.5

(a) Tang. - tangential; HC - high-coupling area; Jct. - junction of coupling and wheel mid-radius.
(b) Exposed 300 hours without failure.

TABLE 9. EFFECT OF CREEP TEMPERATURE AND STRESS ON THE RETAINED TENSILE PROPERTIES OF A Ti-7Al-12Zr COMPRESSOR-WHEEL FORGING GIVEN SINGLE AND DUPLEX ANNEALS(20)

300-hr Creep Exposure Condition			Retained Room-Temperature Properties			
Temperature, F	Stress, ksi	Deformation, percent	F_{tu}, ksi	F_{ty}, ksi	Elongation, percent	Reduction of Area, percent
			Annealed 1600 F/4 hr, AC			
RT	-	-	133	121	25	37
800	60	0.07	134	127	16	20
850	57.5	0.14	136	127	5	6.3
950	40	0.24	137 (a)	125 (a)	6.5 (a)	7.2 (a)
1050	20	0.20	138	127	5.5	9.4
1100	15	0.34	141	130	12	18
			Annealed 1750 F/1 hr, AC + 1300 F/8 hr, AC			
RT	-	-	132	123	18	35
800	60	0.07	135 (a)	126 (a)	20 (a)	19 (a)
850	57.5	0.19	138	130	21	25
950	40	0.33	137	126	6	7
1050	20	0.20	139 (a)	125 (a)	15 (a)	23 (a)
1100	15	0.22	140	130	7.5	10.2

(a) 0.050 inch machined from specimen diameter after exposure.

TABLE 10. EFFECT OF SOLUTION TEMPERATURES ON DUCTILITY OF Ti-679(17)

Solution Temperature, F(a)	Ultimate Tensile Strength, ksi	Yield Strength, ksi	Elongation, percent	Reduction of Area, percent
1700	194.6	169.0	6.0	23.7
1675	186.9	168.3	--	--
1625	176.8	151.5	12.0	43.0
1600	176.2	152.0	12.0	41.0
1575	154.8	118.1	19.0	41.8
1550	155.8	104.7	18.0	39.1

(a) All samples water quenched from temperature and not aged.

TABLE 11. AGING RESPONSE OF Ti-679 QUENCHED AT VARIOUS RATES (ALL SAMPLES SOLUTION TREATED AT 1650 F)(17)

Sample	Aging Temperature (24 hrs), F	Quench Rate	Ultimate Tensile Strength, ksi	Yield Strength, ksi	Elongation, percent	Reduction of Area, percent
As forged	--	--	151.2	136.5	14.0	49.9
15-38	930	Furnace cooled	143.7	132.1	11.0	23.1
15-39	--	Furnace cooled	143.8	133.0	11.0	25.8
15-3	930	Air cooled	167.3	149.6	17.5	44.4
15-28	--	Air cooled	159.8	142.8	16.0	47.4
15-13	930	Water quenched	199.6	180.0	10.0	32.9
15-22	--	Water quenched	176.8	151.5	12.0	43.0

TABLE 12. TENSILE PROPERTIES ROLLED BAR, AIR COOL VERSUS OIL QUENCH(17)

		Air Cooled from 1650 F				Oil Quenched from 1650 F			
Material	Heat-treatment Section Size, in.	Ultimate Tensile Strength, ksi	Yield Strength, ksi	Elong., percent	R.A., percent	Ultimate Tensile Strength, ksi	Yield Strength, ksi	Elong., percent	R.A. percent
Rolled bar	3 (edge)	151.0	--	21	42	170.0	142.0	18	40
(originally	3 (center)	150.5	127.5	18	34	169.0	139.0	16	34
3-1/2-in.diam.	2	158.5	131.5	16	31	174.0	145.0	14	32
	1-1/2	160.0	135.5	17	29	179.5	147.0	18	33
	1	160.0	134.0	17	31	182.0	150.0	14	31
	1/2	166.0	147	17	30	194.0	163.0	12	29

TABLE 13. AVERAGE TENSILE PROPERTIES OF IMI 679 COMPRESSOR-WHEEL FORGINGS[a]

Forging	Temperature F	0.2 Percent Yield Strength, ksi	Ultimate Tensile Strength, ksi	Elongation, percent	Reduction of Area, percent	Reference
1 Hammer forging,	70	130.2	146.9	12.9	32.4	24
stock 8-1/8-in. billet,	400	105.1	129.6	15.5	40.7	
source: TMCA	550	96.8	121.4	15.8	39.8	
	800	82.2	106.7	15.4	38.9	
	900	78.7	103.4	16.7	49.4	
	1000	78.7	101.9	15.3	39.2	
2 Hammer forging,	70	141.8	156.5	13.2	36.4	24
stock 8-1/8-in. billet,	900	90.7	111.7	15.4	51.9	
source: TMCA						
3 Press forging,	70	137.3	151.8	13.5	32.8	24
stock 8-1/8-in. billet,	550	95.2	121.0	12.5	34.4	
source: TMCA	900	83.0	105.0	16.0	41.5	
	1000	80.3	102.8	16.5	42.4	
4 Press forging,	70	137.3	153.4	14.4	37.5	24
stock 8-1/8-in. billet,	550	102.5	125.8	15.5	46.9	
source: IMI	900	83.0	105.0	16.0	41.5	
	1000	79.0	102.0	16.0	45.5	
5 Press forging	70	136.1(b)	161.2	15.2	42.5	25
stock 8-in. billet,	840	81.3(b)	114.5	18.6	52.8	25
source: IMI						

(a) Heat treatment, Forgings 1-4, 1650 F/1 hr, AC + 930 F/24 hr, AC.
Forging 5, 1650 F/1 hr, Oil Q+ 930 F/24 hr, AC.

(b) 0.1 percent proof stress.

TABLE 14. ROOM-TEMPERATURE NOTCHED-TENSILE PROPERTIES OF TITANIUM ALLOY IMI 679 FORGING

Forging Type	Position	Direction	Theoretical Stress Concentration Factor, K_t	Notched Tensile Strength, ksi	$\frac{NTS}{TS}$	Reference
Large compressor disk[(a)]	Rim	Radial	3.0	243	1.52	25
	Rim	Axial	3.0	245	1.53	25
	Rim	Tangential	3.0	246.5	1.55	25
	Web	Radial	3.0	246	1.47	25
	Web	Tangential	3.0	244.5	1.50	25
F-104 fuselage ring fitting[(b)]	Flange	Longitudinal Grain Direction	3.9	136		26
	Edge		3.9	139		26
	Mid-radius		3.9	142		26
	Center		3.9	144		26

(a) Disk made from 8-in-diameter x 12-in-long billet, upset forged to a flat cheese at 1650 F, pressed between shaped dies at 1650 F, heat treated for 1 hour at 1650 F, oil quenched, aged for 24 hours at 930 F, and air cooled.

(b) Cut weights of material for four forgings, 108 to 111 lb ea. Forging furnace temperature 1675 F. Average temperature on dies: draw 1540 F, bend 1545 F, 1st finish 1480 F, 2nd finish 1550 F. Heat treatment: 1 hour at 1650 F, fan cool, aged for 24 hours at 930 F, and air cooled.(22)

TABLE 15. NOTCH TIME FRACTURE TESTS (70 F, k_t = 3.8) OF Ti-679 COMPRESSOR WHEEL FORGINGS(24)

All forgings held 1650 F/1 hr, AC, + 930 F/24 hrs, AC.

Location,	Direction	Hours under Test at Indicated Stress				
		170 ksi	180 ksi	190 ksi	200 ksi	210 ksi
Coupling	Axial	5.2	5.3 failed	--	--	--
Coupling	Axial	5.0	5.0	5.2	0.2 failed	--
Rim	Tangential	5.1	5.4	5.0	5.2	1.3 failed
Web	Radial	5.1	5.0	5.0	1.6 failed	--
Web	Radial	--	5.7	3.8 failed	--	--
Rim	Tangential	--	5.7	4.9 failed	--	--
Rim	Tangential	--	5.7	4.6 failed	--	--
Web	Radial	--	5.6	0.6 failed	--	--
Rim	Tangential	--	5.2 failed	--	--	--
Web	Radial	--	5.0	0.3 failed	--	--
Rim	Tangential	--	5.0	0.2 failed	--	--
Web	Radial	--	5.2	0.1 failed	--	--

TABLE 16. CREEP PROPERTIES OF ALLOY 679 COMPRESSOR-WHEEL FORGINGS(a)

Forging(b)	Temperature, F	Stress, ksi	Time to 0.1 percent plastic Deformation, hours	Time to 0.2 percent plastic Deformation, hours	Plastic Deformation in 150 hours, percent	Plastic Deformation in 100 hours, percent	Duration of test, hours	Total Creep, percent	Reference
1	850	65.0	64	184	0.158		165	0.160	24
	850	65.0	26	150	0.2		166	0.200	24
	850	65.0	70	875	0.13		1010	0.240	24
	900	55.0	90	240(c)	0.13		166	0.130	24
	900	55.0	20	130	0.21		166	0.210	24
	900	55.0	60	625	0.14		1090	0.236	24
	950	45.0	20	180	0.18		166	0.185	24
	950	45.0	25	220	0.17		1000	0.796	24
	1000	35.0	10	90	0.34		150	0.392	24
2	850	65.0	58	200(c)			150	0.144	24
	850	65.0					1000	0.408	24
	900	55.0					150	0.164	24
	900	55.0					1000	0.364	24
	950	45.0					150	0.240	24
	950	45.0					1000	1.668	24
3	850	65.0							
	900	55.0					150	0.152	24
	900	55.0					150	0.256	24
	900	55.0					150	0.152	24
	950	45.0					150	0.196	24
	950	45.0					150	0.679	24
	950	45.0					150	0.236	24
	1000	35.0					150	0.264	24
							150	0.980	24
4	850	65.0					150	0.128	24
	900	55.0					150	0.212	24
	900	55.0					150	0.192	24
	900	55.0					150	0.156	24
	900	45.0					150	0.372	24
	950	45.0					150	0.328	24
	950	45.0					150	0.160	24
	1000	35.0					150	0.340	24
5	750	78.5				0.124			25
	750	78.5				0.088			25
	750	78.5				0.119			25

(a) Heat treatment, Forgings 1-4, 1650 F/1 hr, AC + 930 F/24 hr, AC. Forging 5, 1650 F/1 hr, Oil Q + 930 F/24 hr, AC

(b) See Table 13 for description of forgings.

(c) Extrapolated.

TABLE 17. ELEVATED-TEMPERATURE STRESS-RUPTURE PROPERTIES OF Ti-679 COMPRESSOR-WHEEL FORGINGS(17)
Heat Treatment: 1650 F/1 hr, AC + 930 F/24 hr, AC.

Location	Direction	Temp., F	Stress, ksi	Rupture Life, hr	Elongation, percent
Rim	Tangential	950	60	727	23.9
Rim	Tangential	950	60	1468	17.3
Web	Radial	950	60	879	22.6
Rim	Tangential	950	80	153	21.3
Rim	Tangential	950	80	215	10.9
Web	Radial	950	80	199	22.6
Web	Radial	950	80	34	14.6
Web	Radial	950	80	199	25.3
Rim	Tangential	1000	65	154	17.3
Rim	Tangential	1000	65	123	27.9
Web	Radial	1000	65	108	27.9
Web	Radial	1000	65	151	27.9

TABLE 18. STABILITY OF Ti-679 ALLOY COMPRESSOR-WHEEL MATERIAL AFTER SELECTED CREEP EXPOSURES(17)
Heat Treatment: 1650 F/1 hr, AC + 930 F/24 hr, AC

		Creep Exposure				Postcreep Tensile Properties			
Location	Direction	Temp., F	Stress, ksi	Time, hr	Plastic Deformation, %	Y.S. 0.2% ksi	U.T.S., ksi	Elongation, %	R.A. %
Typical Unexposed Properties		-	-	-	-	138.0	155.0	13.0	30.0
Web	Radial	800	75	150	0.15	141.2	155.5	16.0	36.7
Web	Radial	800	75	150	0.16	136.7	149.9	12.0	25.5
Rim	Tang.	850	65	150	0.17	140.6	154.2	14.0	32.7
Rim	Tang.	850	65	150	0.15	141.0	152.9	13.0	29.5
Rim	Tang.	850	65	150	0.13	142.5	156.4	12.0	29.5
Rim	Tang.	850	65	150	0.14	151.0	166.1	14.0	36.2
Rim	Tang.	850	65	150	0.15	144.0	152.9	13.0	29.5
Rim	Tang.	850	65	1000	0.31	138.1	149.9	15.0	30.8
Rim	Tang.	850	65	1000	0.21	141.7	156.0	13.0	28.7
Rim	Tang.	900	50	150	0.13	141.4	157.6	14.0	25.4
Rim	Tang.	900	50	150	0.19	141.2	154.0	10.0	18.3
Coupling	Axial	900	55	150	0.26	137.2	150.3	14.0	31.6
Coupling	Axial	900	55	150	0.21	134.7	149.0	14.0	36.2
Web	Radial	950	45	150	0.24	143.6	157.7	7.0	7.9
Web	Radial	950	45	150	0.33	136.4	150.7	7.0	6.3
Web	Radial	900	55	150	0.15	147.1	161.3	12.0	27.5
Web	Radial	900	55	150	0.19	138.4	153.5	10.0	23.4
Rim	Tang.	900	55	150	0.20	141.0	154.2	12.0	25.4
Rim	Tang.	900	55	150	0.16	140.0	154.2	13.0	27.5
Rim	Tang.	900	55	150	0.16	142.0	157.2	12.0	22.6
Rim	Tang.	900	55	1000	0.36	142.1	156.8	15.0	28.9
Coupling	Axial	950	45	150	0.68	133.3	149.4	12.0	17.7
Coupling	Axial	950	45	150	0.37	137.6	151.5	9.0	13.9
Rim	Tang.	950	45	150	0.26	142.7	154.4	10.0	19.8
Rim	Tang.	950	47	150	0.16	140.5	155.0	14.0	28.8
Rim	Tang.	950	45	150	0.24	140.9	156.4	14.0	32.3
Rim	Tang.	950	45	1000	1.67	135.5	149.2	6.0	8.7
Rim	Tang.	1000	35	150	0.88	135.4	147.4	7.0	13.2
Rim	Tang.	1000	35	150	0.34	139.6	151.9	5.0	9.4

TABLE 19. RECOMMENDED SOLUTION-TREATMENT TEMPERATURES FOR IMI TITANIUM 680 FORGINGS HAVING A RATIO OF MAXIMUM TO MINIMUM SECTION THICKNESS NOT EXCEEDING 4:1(7)

Thickness of Predominant Section, in.	Solution-Treatment Temperature, F(a)	
	Water Quenching	Oil Quenching
1/4	1490	1490
1/2	1495	1495
3/4	1500	1510
1	1510	1515
1-1/2	1510	1515
1-3/4	1515	1525
2	1515	1525
3	1535	1545
4	1545	1555
4-1/2	1535	1545
5	1525	1535
8(b)	--	1560

(a) After solution heat treatment all sizes should be aged 24 hr at 930-1110 F. Aging at 930 F is recommended because optimum creep properties are produced after aging at this temperature.

(b) Billet. After quench, age 24 hr at 1020 F.

TABLE 20. TYPICAL ROOM-TEMPERATURE TENSILE PROPERTIES OF IMI ALLOY 680(7)

Material	Method of Selecting Test Specimens	Heat Treatment	Tensile Properties			
			0.1 percent Proof Stress, ksi	Tensile Strength, ksi	Elongation, percent	Reduction of Area, percent
1-in-diam. rolled rod	Heat treated in full section, longitudinal test	1520 F/1 hr, AC + 930 F/24 hr, AC	172.5	190.4	16	50
3-1/2-in. diam. rolled bar	Heat treated in full section, transverse test	1520 F/2 hr, WQ + 930 F/24 hr, AC	165.8	194.9	9	26
5-1/2 x 4-in. forged bar	Heat treated in full section, transverse test	1530 F/4 hr, WQ + 930 F/24 hr, AC	159.0	190.4	10	27
12 x 5-in. forged bar	Heat treated as transverse slice, transverse test	1480 F/1 hr, WQ + 930 F/24 hr, AC	152.3	179.2	9	22

TABLE 21. TYPICAL ELEVATED-TEMPERATURE TENSILE PROPERTIES OF FULLY HEAT TREATED IMI ALLOY 680(7)

Temp., F	0.1 Percent Proof Stress, ksi	Tensile Strength, ksi	Elong., percent	R.A., percent
68	167.8	196.9	15	44
392	127.7	161.5	19	53
572	121.8	155.4	19	55
752	110.9	149.6	17	56
842	108.9	142.0	16	52
932	101.0	138.0	16	54

TABLE 22. TENSILE PROPERTIES ON SAMPLES CUT FROM A COMPRESSOR-DISK FORGING OF IMI TITANIUM 680(7)

13-in. diameter with a 1-in-thick web

Sample Position	0.1 Percent Proof Stress, ksi	Tensile Strength, ksi	Elongation, percent	Reduction of Area, percent
Axial in bore	-	172.9	13	-
Tangential in bore	162.2	185.9	16	47
Radial in diaphragm	163.5	187.5	13	47
Tangential in rim	168.0	187.5	13	41
Radial in rim	-	182.3	13	33

TABLE 23. TENSILE PROPERTIES ON SAMPLES CUT FROM A STEERING-ARM FORGING OF IMI TITANIUM 680(7)

15 in. long x 6 in. wide

Sample Position	0.2 Percent Proof Stress, ksi	Tensile Strength, ksi	Elongation, percent	Reduction of Area, percent
1	169	188	11	35
2	174	186	8	37
6	183	198	11	33
8	184	196	10	37
10	168	180	11	30
12	178	190	9	30
12b	176	190	11	23

TABLE 24. EFFECT OF NOTCH CONCENTRATION FACTOR ON NTS/TS RATIO OF FULLY HEAT TREATED ROD OF IMI ALLOY 680(7)

Notch Concentration Factor, K_t	Notched Tensile Strength, ksi	$\frac{NTS}{TS}$
1.7	275.5	1.44
3.0	266.6	1.40
~5.75	224.0	1.17
~7.75	221.8	1.16

TABLE 25. RELATION BETWEEN NOTCHED AND UNNOTCHED TENSILE STRENGTH OF IMI TITANIUM 680(7)

Solution Temp., F	Tensile Strength, ksi	Elongation, percent	Reduction of Area, percent	Notched Tensile Strength, ksi	$\frac{NTS}{TS}$
1380	175.8	14	43	260	1.48
1430	180.3	12	33	260	1.44
1470	184.1	12	30	253	1.37
1520	197.1	10	16	244	1.24
1560	228.0	3	3	193	0.85
1610	233.0	2	3	157	0.68
1650	241.2	2	2	168	0.70

TABLE 26. STRESS TO PRODUCE 0.1 PERCENT TOTAL PLASTIC STRAIN in 100 HOURS IN IMI 680(7)

Temp., F	Estimated Stress to Give 0.1 Percent Total Plastic Strain in 100 Hours, ksi
70	165
300	135
390	130
570	115
750	80
840	45
930	13

TABLE 27. TENSILE AND CREEP PROPERTIES OF IMI TITANIUM EX 684 ENGINE-COMPRESSOR DISK(8)

Tensile and creep properties of two 18-in-diam. disks, with a web thickness of 1-1/2 in. and a rim thickness of 3 in. each weighing 100 lb, heat treated 1915 F/1-1/2 hr, OQ + 930 F/24 hr, AC.

		Tensile Properties						Creep Data, Strain in 100 Hours at 970 F and 44.8 Ksi	
Position of Test Piece	Test Temp., F	0.1 Percent Proof Stress, ksi	Tensile Strength, ksi	Elongation[a], percent	Reduction of Area, percent	Notched Tensile Strength (K_t = 3), ksi	$\frac{NTS}{TS}$	Initial Plastic, percent	Total Plastic, percent
				Disk Forged at 1920 F					
Tangential, web	70	125	143	16	24	229	1.6	0.013	0.186
Tangential, rim	70	128	143	13	23	227	1.59	nil	0.092
	970	68.8	90.0	18	38	-	-	-	-
Radial, web	970	-	-	-	-	-	-	nil	0.11
				Disk Forged at 1800 F					
Tangential, web	70	127	143	15	24	221.5	1.52	nil	0.071
Tangential, rim	70	121	135.5	14	25	219.5	1.58	nil	0.068
	970	69.2	90.6	16	35	-	-	-	-
Radial, web	970	-	-	-	-	-	-	nil	0.056

TABLE 28. TENSILE PROPERTIES OF IMI TITANIUM EX 684 ENGINE-COMPRESSOR DISK(8)

13-in-diam. x 1-in-rim thickness, weight 25 lb, forged to 13-1/4-in-diam. cheese at 1800 F and stamped to disk at 1885 F.

			Tensile Properties					
Sample Position	Heat Treatment	Test Temp., F	0.1 percent Proof Stress, ksi	Tensile Strength, ksi	Elong., percent	Reduction of Area, percent	NTS (K_t=3), ksi	$\frac{NTS}{TS}$
Tangential, hub and web	1915 F/3/4 hr, AC + 930 F/24 hr, AC	Room	132.5	150.5	11	21	235	1.56
	1915 F/3/4 hr, OQ + 930 F/24 hr, AC	Room	137	156	12	24	240	1.54
Radial, web	1915 F/3/4 hr, AC + 930 F/24 hr, AC	Room	132.5	150.5	10	22	240	1.6
	1915 F/3/4 hr, OQ + 930 F/24 hr, AC	Room	137	156	13	23	240	1.54
Axial, hub (tensometer tests)	1915 F/3/4 hr, AC +930 F/24 hr, AC	Room	136	143.5	8	20	237.5	1.66
	1915 F/3/4 hr, OQ + 930 F/24 hr, AC	Room	136	150	10	25	237.5	1.57
Tangential, test ring	1915 F/3/4 hr, AC + 930 F/24 hr, AC	970	60.2	85.4	15.6	27	-	-
Tangential, hub	1915 F/3/4 hr, AC +930 F/24 hr, AC	970	69.0	88.2	14.5	25	-	-
Radial, web	1915 F/3/4 hr, AC + 930 F,24 hr, AC	970	66.7	87.5	15.0	23	-	-

TABLE 29. TENSILE AND CREEP PROPERTIES OF IMI TITANIUM EX 684 ENGINE-COMPRESSOR DISC(8)

13-in-diam.x 1-in. rim thickness, weight 25 lb, forged to 13-1/4-in. diam cheese at 1800 F, stamped to disk at 1800 F.

			Tensile Properties						Creep Data
Sample Position	Heat Treatment	Test Temp., K	0.1 Percent Proof Stress, ksi	Tensile Strength, ksi	Elong., percent	R.A., percent	NTS $(K_t=3)$, ksi	NTS/TS	Strain in 100 Hours at 940 F and 44.8 ksi, Total, percent
Tangential, rim	1915 F/3/4 hr, AC + 930 F/24 hr, AC	Room	123.0	140.5	11	17	220.0	1.56	0.085
Radial, web	1915 F/3/4 hr, AC + 930 F/24 hr, AC	Room	123.0	143.5	13	17	224.0	1.56	-
Tangential, rim	1915 F/3/4 hr, OQ + 930 F/24 hr, AC	Room	128.5	147.5	10	20	233.0	1.59	0.12
Radial, web	1915 F/3/4 hr, OQ + 930 F/24 hr, AC	Room	123.0	149.0	12	20	229.0	1.54	-
Tangential, web	1915 F/3/4 hr, AC + 930 F/24 hr, AC	570	74.6	98.9	14	35	-	-	-
		850	69.5	89.5	14	22	-	-	-
		970	63.1	82.5	15	30	-	-	-
Tangential, web	1915 F/3/4 hr, OQ + 930 F/24 hr, AC	570	81.3	107	14	33	-	-	-
		850	76.4	104	20	35	-	-	-
		970	72.1	94.5	18	38	-	-	-

TABLE 30. CREEP PROPERTIES OF IMI EX 684 ENGINE COMPRESSOR DISK SAMPLES(8)

Test pieces taken tangentially from the rim

	Creep-Test Data			Total Plastic Strain, percent	
Heat Treatment	Temperature, F	Stress, ksi	Initial Plastic Strain, percent	50 hours	100 hours
1915 F/3/4 hr, AC + 930 F/24 hr, AC	970	44.8	nil	0.051	0.072
1915 F/3/4 hr, OQ + 930 F/24 hr, AC	970	44.8	nil	0.035	0.059

TABLE 31. EFFECTS OF 975 F EXPOSURE ON THE ROOM-TEMPERATURE TENSILE PROPERTIES OF IMI EX 684(8)

Exposure Time, hours(a)	0.1 Percent Proof Stress, ksi	Tensile Strength, ksi	Elongation, percent	Reduction in Area, percent	Notched Tensile Strength, ksi (K_t = 3)	$\frac{NTS}{TS}$
0	137	152	16	23	242	1.6
100	140	157	14	21	233	1.49
300	143	160	9	19	213	1.33
1000	142	159	9	12	222	1.4

(a) 0.5-in-diameter rod, initially held 1915 F/3/4 hr, OQ + 930 F/24 hr, AC.

TABLE 32. EFFECT OF SOLUTION TREATMENT TIME ON THE TENSILE PROPERTIES OF FORGED, 1/2-INCH-THICK PLATES OF IMI EX 700(18)

	Solution Treatment(a)	
Properties	1 hr at 1520 F(b)	5 hrs at 1520 F(b)
0.2 % Proof Stress, ksi	187.7	180.0
Tensile Strength, ksi	204.7	202.7
Elongation, percent	8	14.3
Reduction of Area, percent	18	25.3
Notched Tensile Strength, ksi	241.3	261.3
NTS/TS ratio	1.18	1.29

(a) Values given represent averages of samples from three separate heats

(b) All samples oil quenched from 1520 F and aged 24 hours at 930 F followed by air cooling

TABLE 33. TENSILE PROPERTIES OF UPSET FORGINGS OF IMI EX 700(18)

Forging Thickness, inches	Sample Location	Smooth Tensile Properties				Notched Tensile Strength, ksi	NTS/TS
		0.2 % Offset Yield Strength, ksi	Ultimate Strength, ksi	Elong., percent	Reduction of Area, percent		
		Solution Treated 1520 F, OQ + 24 Hours, 930 F, AC					
0.5	Rim, radial	187	209	11	25	246	1.18
	Center	189	210	10	28	242	1.16
1.0	Rim, radial	184	207	13	23	244	1.18
	Center	187	207	9	24	248	1.20
1.75	Rim, edge	181	200	11	26	270	1.36
	Rim, middle	179	199	10	19	246	1.23
	Center, edge	179	202	4.5	6	246	1.23
	Center, middle	180	199	12	29	276	1.39
		Solution Treated 1560 F, OQ + 24 Hours, 930 F, AC					
1.5	Rim, radial, edge	186	210	11	23	224	1.07
	Rim, radial, middle	183	210	6	17	242	1.15
	Center, edge	184	210	6	14	215	1.03
	Center, middle	181	208	14	30	238	1.14
2.25	Rim, edge	184	214	4	6	258	1.20
	Rim, middle	179	203	[illegible]	11	264	1.30
	Center, edge	177	200	2.5	2	233	1.16
	Center, middle	177	206	8	13	262	1.27

TABLE 34. EFFECT OF SECTION SIZE AND COOLING RATE FROM SOLUTION TEMPERATURE ON PROPERTIES OF HYLITE 50(21)

Section Size	Cooling Method	Average Tensile Strength psi	Average Elong., percent
5/8 in. diam.	Vermiculite	169,000	16
	Air	176,000	15
	Oil quench	207,000	7.5
	Water quench	210,000	7.5
2 in. square	Air	172,000 (outside)	14
	Water quench	197,000 (outside)	3.5
4 in. square	Water quench	166,000 (center)	14
		134,000	5

Note: Standard heat treatment: solution treat at 1650 F; air cool; age 24 hr at 930 F

TABLE 35. TENSILE PROPERTIES OF HYLITE 50 SAMPLES FROM DISK FORGING(21)

Position of Test Piece	Yield Strength (0.1 Percent Offset), psi	Tensile Strength, psi	Elong., percent	Reduction of Area, percent
Longitudinal, hub	--	174,600	12.0	19 to 25
Radial, hub	--	170,900	14.8	31 to 33
Longitudinal, periphery	128,000	167,000	12.5	27
Radial, mid-radius	148,000	168,500	14.5	35
Tangential, hub	128,000	166,200	12.5	27
Tangential, periphery	139,000	164,800	15.9	31

Note: Izod impact strength at a radial-mid-radius position is 14 ft-lb. Heat treatment: 2 1/4 hr at 1650 F; air cool; aged 24 hr at 930 F. Disk was 24 in. in diameter.

TABLE 36. CREEP-RUPTURE PROPERTIES OF HYLITE 50(10)

Temperature, F	Time, Hours	Stress to Produce a Total Plastic Strain of 0.10 Percent, ksi	Stress to Produce Rupture, ksi
570	30	105.3	--
	100	105.0	--
	300	104.2	--
	1000	103.1	--
750	30	82.8	123.2
	100	75.0	122.0
	300	67.2	121.0
	1000	59.4	117.7
840	30	45.9	112.[illegible]
	100	37.0	109.5
	300	29.1	103.1
	1000	20.2	87.4
930	30	--	85.2
	100	8.95	68.3
	300	--	49.3
	1000	--	32.5

TABLE 37. TYPICAL TENSILE PROPERTIES OF 1-INCH-DIAMETER WROUGHT BAR OF HYLITE 51 TITANIUM ALLOY(10)

				Air Cooled and Aged				
Temperature, F	70	210	390	570	750	930	1020	1110
0.20 Percent Proof Stress, ksi	181	163	134	116	108.3	97.5	87.6	66.8
Ultimate Tensile Strength, ksi	202	189	166	152	141	133.5	125.5	109.8
Elongation, percent	10.5	11.0	13.5	14.5	13.5	15.0	16.5	22.0
Reduction of Area, percent	27	29	38	38	41	55	59	65
				Oil Quenched and Aged				
Temperature, F	70		390	570		930	1020	1110
0.20 Percent Proof Stress, ksi	188		142	120		98.8	87.9	72.9
Ultimate Tensile Strength, ksi	222		187	168		150	124	109
Elongation, percent	6.5		3.0	12.0		14.5	17.0	22.0
Reduction of Area, percent	8		9	43		53	62	72

TABLE 38. TYPICAL ROOM TEMPERATURE PROPERTIES OF A 3-INCH-SQUARE BILLET OF HYLITE 51 TITANIUM ALLOY(10)

	Air Cooled and Aged		Oil Quenched and Aged	
	Surface	Center	Surface	Center
0.2 Percent Proof Stress, ksi	174	161	187	177
Ultimate Tensile Strength, ksi	186	172	212	196
Elongation, percent	16.0	15.0	10.5	12.5
Reduction of Area, percent	43.0	40.0	24.0	37.0

Note: Heat treatments were not specified, but material may be assumed to have been annealed at 1650 F for 1 hour per inch of cross section, cooled to room temperature, and aged 24 hours at 930 F.

TABLE 39. TENSILE AND IMPACT PROPERTIES OF HYLITE 51 UNDERCARRIAGE FORGING(10)

Heat treatment: 1650 F/3 hr, AC + 930 F/24 hr, AC.

Test Piece	Test Piece Direction	Ultimate Tensile Strength, ksi	0.2 Percent Proof Stress, ksi	Elongation, percent	Reduction of Area, percent	Izod, ft-lb.
1	Tangential	191	176	12.5	24.0	--
2	Tangential	187	171	12.5	24.0	--
3	Tangential	181.5	165	15.0	35.0	--
4	Longitudinal	178.5	163	15.0	33.7	--
6	Longitudinal	182	166	15.0	37.0	--
8	Longitudinal	181	164	15.0	43.5	--
9	Transverse	180	161	12.5	37.0	--
10	Longitudinal	183.5	168.5	13.0	35.7	--
11	Longitudinal	184	167	15.0	40.5	--
12	Longitudinal	185.5	167.5	13.5	40.5	--
13	Longitudinal	--	--	--	--	7,8,7
14	Transverse	181.5	164	13.5	34.0	--
15	Tangential	188.5	172	12.5	31.0	--
16	Tangential	187.5	169	13.5	37.0	--
17	Longitudinal	--	--	--	--	8,8,6
18	Longitudinal	178	163	16.0	40.5	--
19	Oblique	180	162	15.0	40.5	--
20	Longitudinal	180.5	163	15.0	40.5	--
21	Longitudinal	179	164	15.0	40.5	--
22	Longitudinal	183	167.5	16.0	43.5	--
23	Oblique	179	162	16.0	37.0	--
24	Longitudinal	--	--	--	--	11,9,8
25	Longitudinal	176.5	165	15.0	39.7	--
26	Longitudinal	--	--	--	--	[illegible]
27	Longitudinal	180	164	13.5	43.5	--
28	Longitudinal	--	--	--	--	6,6,[illegible]
29	Transverse	186.5	162	15.0	34.0	--

TABLE 40. CREEP PROPERTIES OF TITANIUM ALLOY HYLITE 51.(10)

1-inch-diameter bar in the air cooled and aged condition.

Temperature, F	Time, Hours	Stress to Produce 0.10 Percent Total Plastic Strain, ksi
750	100	90.6
750	300	83.5
750	1000	72.7
750	3000	(a)
840	100	44.8
840	300	31.4

(a) 78.5 ksi to produce 0.20 percent plastic strain in 3000 hours.

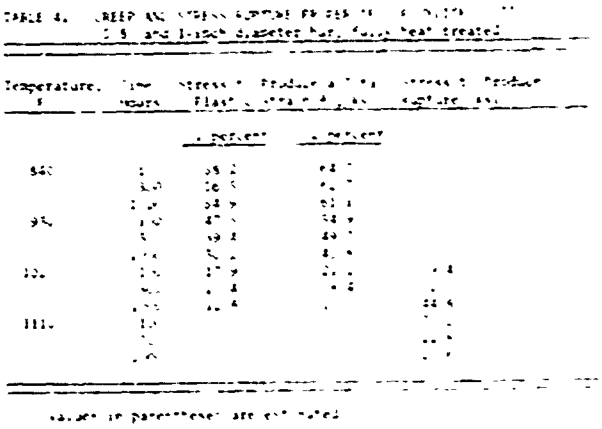


TABLE 42. YOUNG'S MODULUS OF HYLITE 55[(11)]
(1-inch-diameter bar, fully heat treated)

Temperature, F	Modulus, 10^6 psi
70	16.7
210	16.1
390	15.4
570	14.6
750	13.9
930	13.1
1110	12.4
1290	11.6

TABLE 43. TYPICAL TENSILE PROPERTIES OF FORGED HYLITE 60 COMPRESSOR DISK(4)(a)

Temperature, F	0.2 Percent Yield Strength, ksi	Ultimate Tensile Strength, ksi	Elong, percent	Reduction of Area, percent
70	130	150	11	30
600	90	116	12	36
800	85	113	13	39
1000	78	106	15	43

(a) 1830 F/1 hr, AC + 1020 F/24 hr, AC.

TABLE 44. CREEP PROPERTIES FROM A 24-INCH-DIAMETER COMPRESSOR-DISK FORGING OF HYLITE 60(10)(a)

Temperature, F	Time, Hours	Stress to Produce a Total Plastic Strain, ksi: 0.10 Percent	Stress to Produce a Total Plastic Strain, ksi: 0.20 Percent
840	100	59.8	80.6
840	300	52.0	77.3
840	1000	47.0(b)	68.4
1020	100	47.0	--
1020	300	40.7	--

(a) Fully heat treated.
(b) Estimated.

TABLE 45. ESTIMATED STRESSES REQUIRED TO PRODUCE TOTAL PLASTIC CREEP STRAINS UP TO 1.0 PERCENT AT 750 F AND 840 F IN 5/8-INCH-DIAMETER HYLITE 60 SWAGED ROD(30)

Heat treated prior to Machining--1830 F/0.5 hr, AC + 1020 F/24 hr, AC. After machining and before polishing, stress relieved 1020 F/0.5 hr.

Strain, percent	Stresses Required in Specified Times, ksi: 100 Hr	200 Hr	300 Hr	500 Hr
	Creep Tests at 750 F			
0.05	67.1	63.8	60.5	56.0
0.1	80.6	78.5	76.1	71.6
0.2	94.0	93.0	91.9	89.6
0.3	100.8	99.7	98.6	97.5
0.5	106.4	105.3	105.3	105.3
1.0	112.0	112.0	100.9	109.8
	Creep Tests at 840 F			
0.05	52.6	49.3	48.2	45.9
0.1	65.1	61.6	60.5	57.1
0.2	78.4	76.1	73.9	71.7
0.3	86.3	84.0	82.9	79.5
0.5	95.1	93.0	91.8	89.6
1.0	105.2	104.1	103.0	101.9

TABLE 46. TYPICAL POSTCREEP TENSILE RESULTS OF HYLITE 60[4]
Heat treated 1830 F/1 hr, AC + 1020 F/24 hr, AC

Creep Exposure			0.2 Percent Yield Strength, ksi	Ultimate Tensile Strength, ksi	Elongation, percent	Reduction of Area, percent
Temperature, F	Stress, ksi	Time, Hours				
	None		133.0	150.0	11.0	32.0
900	50	150	145.0	162.3	14.0	29.4
1000	40	150	143.5	159.0	12.0	26.0
1050	30	150	141.5	155.0	7.0	13.1

TABLE 47. TYPICAL TENSILE PROPERTIES OF HYLITE 65 HEAT TREATED 1-INCH-DIAMETER BAR[10]

Temperature, F	70	210	390	570	750	930	1110	1290
0.2 Percent Proof Stress, ksi	136.0	121.0	97.5	87.4	83.5	75.2	69.5	37.0
Ultimate Tensile Strength, ksi	155.0	141.0	121.0	110.1	104.4	97.2	91.5	63.6
Elongation, percent	15.5	16.0	18.5	18.0	16.0	17.0	21.0	50.0
Reduction of Area, percent	27	49	41	39	39	45	49	64

TABLE 48. CREEP PROPERTIES OF HYLITE 65 HEAT-TREATED 1-INCH-DIAMETER BAR[10]

Temperature, F	Time, Hours	Stress to Produce 0.1 Percent Total Plastic Strain, ksi
750	30	80.6
750	100	78.5
840	30	71.7
840	100	67.2
930	30	58.2
930	100	51.5
960	30	53.8
960	100	46.0

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13 ABSTRACT

This memorandum compares and summarizes the compositions, recommended heat treatments, and basic physical and mechanical properties for a group of 12 relatively new titanium alloys. Most of these were developed for service above 600 F as bar and forging alloys and can be considered as alloys of the "super" alpha class. These include the Ti-6Al-2Sn-4Zr-2Mo, Ti-5Al-5Sn-5Zr, and Ti-7Al-12Zr compositions, which were developed in the United States, as well as the series of IMI-679, -680, -EX 684, and -EX 700 alloys and of Hylite 50, 51, 55, 60, and 65 alloys, all of which were developed in the United Kingdom. In addition, some preliminary data are presented for a silicon-modified version of the Ti-6Al-2Sn-4Zr-2Mo alloy.

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14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Titanium Alloys						
Ti-6Al-2Sn-4Zr-2Mo						
Ti-6Al-2Sn-4Zr-2Mo-Si						
Ti-5Al-5Sn-5Zr						
Ti-7Al-12Zr						
IMI-679 (Ti-2.25Al-11Sn-5Zr-1Mo-0.2Si)						
IMI-680 (Ti-2.25Al-11Sn-4Mo-0.2Si)						
IMI-EX 684 (Ti-6Al-5Zr-1W-0.2Si)						
IMI-EX 700 (Ti-6Al-5Zr-4Mo-1Cu-0.2Si)						
Hylite 50 (Ti-4Al-2Sn-4Mo-0.5Si)						
Hylite 51 (Ti-4Al-4Sn-4Mo-0.5Si)						
Hylite 55 (Ti-3Al-6Sn-5Zr-0.5Si)						
Hylite 60 (Ti-3Al-6Sn-5Zr-0.5Si)						
Hylite 65 (Ti-3Al-5.5Sn-5.5Zr-0.5Mo-0.5Si)						

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